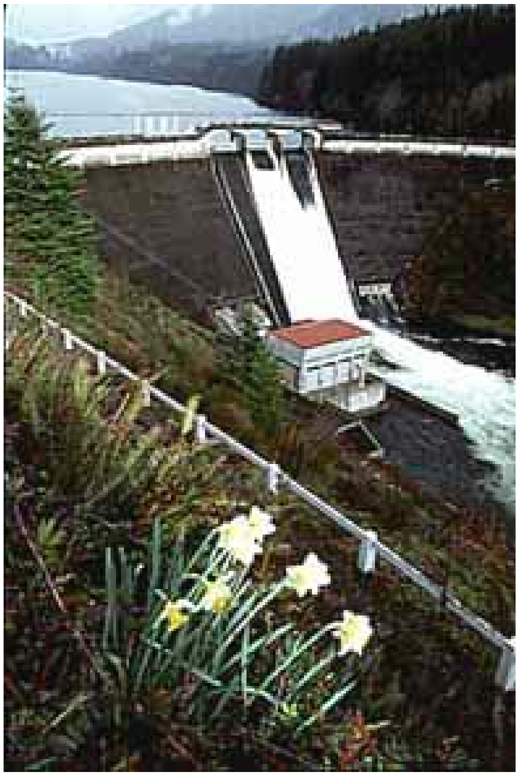
The Impacts of Climate Change on Portland's Water Supply:

An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System



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For

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Executive Summary

Introduction

The initial report of the Intergovernmental Panel on Climate Change (IPCC 1990) and those that have followed (IPCC 2001) conclude that our climate is changing. One of the most important impacts of climate change is on the world's fresh water supplies, caused by increased temperatures, changed precipitation, and shifts in the historic hydrologic cycle. These changes are of particular interest in the Pacific Northwest because of the interplay between precipitation and temperature. Changes in temperature alter the delicate interactions between the amount of precipitation that falls as rain and snow, the accumulation of snow during the winter, and when this snow melts and contributes to streamflow. In addition, climate change can alter the demand for water, with demands increasing during dry, warm periods and decreasing during cool, wet periods. These changes in availability and demand of water will impact municipalities that are charged with providing safe and reliable drinking water. Climate change may impact a municipality's ability to provide water to existing customers and their planning for the future. New sources of water may be required, and the evaluation of these new sources should consider potential climate change.

This study explores the impact that climate change will have on the Bull Run watershed and the Portland Water Bureau's (PWB) ability to provide reliable water to its customers. The study uses a series of linked models to address the potential impacts of climate change. These models simulate three aspects of the process: the climate, the hydrologic cycle, and water supply system management. The results of this study are of particular relevance, as the PWB has recently completed a comprehensive water plan and must now decide which of several potential alternatives it should pursue in continuing to provide safe and reliable water.

Currently, water demands are met with two major dams in the Bull Run watershed and with groundwater. The active capacities of the dams are small (10.2 billion gallons) relative to the flows delivered from their watersheds, thus they refill annually. A number of system expansion alternatives are being considered, including the construction of Dam 3 in the Bull Run basin and the expanded use of groundwater. Dam 3 would double the available surface storage in the basin whereas expansion of the groundwater sources will make the PWB more dependent on subsurface sources. Growing regional water demands will compromise PWB's current ability to provide water reliably during drought events in the future. The decision of how best to supplement the existing water supply with a combination of conservation and new sources is an important decision that will define PWB's role in regional water supply.

Climate Change

In this report, four different Global Circulation Models (GCMs) are used to estimate climate change impacts in the Bull Run watershed: the Department of Energy’s Parallel Climate Model (PCM), the Max Planck Institute’s ECHAM4 model and the Hadley Centre’s HadCM2 and HadCM3 models. These models incorporate a one-percent increase in carbon dioxide per year (the most important green house gas) as the primary driving force for climate change. The climate models used are among the most highly respected models currently available. All four models produce results that suggest summers will be warmer and dryer in the Bull Run watershed. The ECHAM4 model produced the most significant impacts on system reliability.

Monthly changes in temperature generated by these models suggest a general warming trend of about 1.5° C for the decade 2020 and for about 2.0° C the decade 2040 (Figure ES-1). Average monthly temperatures are warmer is every month with the greatest increase in July and August. Precipitation increases in the winter and decreases in the summer. Scientists suggest a high confidence in this estimate of the temperature change, while there is less confidence in exact magnitude of the precipitation change.

Hydrology

The changes in temperature and precipitation have a direct impact on the hydrology of the basin. The Distributed Hydrology, Soil-Vegetation Model (DHSVM) is used to combine historic climate conditions with the climate change signals from the GCMs to obtain climate-altered streamflows (Figure ES-2). The average effect of climate change on the streamflows is that winter flows increase by approximately 15% (2040) and that late spring flows decrease by approximately 30%. The increase in flows historically experienced in April (the spring snowmelt runoff) disappears. These changes are due to an increase in the precipitation falling as rain rather than snow in the winter months, a decrease in the maximum winter snowpack, and a temporal shift in snowpack melt. Although the individual GCM results vary, the general trend is the same : Climate change will cause the Bull Run watershed to become a more rain-driven system, experiencing less late-spring and summer flows.

The change in streamflows from April through September is important since this is the period when demands increase and reservoir storage is used. Figure ES-3 presents the average monthly change in inflows for the current hydrology and the four climate change forecasts. The figure illustrates that, on average, the combined Bull Run River inflows from April to September decrease by 20,000 cfs-days (39,670 acre-ft or 12.9 billion gallons).

Water Supply Impacts

The impacts of climate-altered streamflows on water supply performance are evaluated using the Storage and Transmission Model (STM) considering three climate impacts: 1) changes in water availability, 2) changes in water demand created by climate change and 3) changes in water demand created by anticipated regional growth. Changes in water availability and changes in demand related to regional growth are determined for the entire hydrologic record. Seven specific years were selected for detailed investigations into the impacts on water demand due to climate change. The hydrologic conditions for these years ranged from wet (1968) to average (1966 and 1982) to dry (1952, 1987, 1992 and 1994).

Figure ES-4 summarizes the impacts of climate change on the annual minimum storage of the current system. The average hydrologic impact of climate change on minimum system storage is approximately 1.3 billion gallons, and varies between years. The impact of increased demands due to climate change averages 1.5 billion gallons, and is less variable than the hydrologic impacts. The average impact of climate change on the current system is to require approximately 2.8 billion gallons more storage per year to meet demand. For a year like 1966, the change could be more than 5.5 billion gallons. These impacts reduce the safe yield of the seven years investigated by an average of 21 mgd below current yields. Climate change also has the effect of extending the drawdown period due to lower flows and higher demands, putting the system at risk over longer periods.

The increase in demand associated with anticipated regional growth during the summer reservoir drawdown, without considering climate change, averages 4.1 billion gallons by the year 2020 and 5.5 billion gallons by 2040. When all three factors (climate change on hydrology, climate change on demand, and regional growth) are considered jointly there is, on average, 8.0 billion gallons in reduced inflows and increased demands that must be generated by 2020 and this number increases to 9.6 billion gallons by 2040. In 2040, the most extreme shift results in over 12 billion gallons in increased demands and decreased inflows. This will make the system even more reliant in the future on summer inflows, inflows that will decrease due to climate change.

Management Implications

These increased demands and reduced supplies can be met in several ways in the future, and two are investigated in this report. One alternative is to rely more heavily on groundwater and expand Dam 1 and Dam 2 (denoted as SC2) and another is to build Dam 3, providing approximately 14 billion gallons of addition surface storage (denoted as SC3). If groundwater is developed, the water used to meet increased demands comes primarily from groundwater. Figure ES-5 summarizes the impacts of these alternatives using the ECHAM4 scenario.

For the SC2 scenario, the 2040 climate change impacts associated with the most severe drought on record (1987) uses 9 billion gallons of surface water (leaving a minimum active storage is less than 1.5 billion gallons) and approximately 14 billion gallons of groundwater. This suggests an average summer groundwater pumping rate of approximately 80 mgd for a 180 day drawdown period.

If Dam 3 is built, it provides a significant safety factor for storage into the future (assuming that instream flow requirements on the Bull Run River are not increased). For the 2040 demands, 22 billion gallons of surface water is used to meet the demand during the drawdown period, resulting in a minimum active storage in Bull Run of 7.3 billion gallons. (The dead storage in Dam 1 and Dam 2 is considered to be 6.9 billion gallons)

Water availability and water demand vary significantly between years. Figure ES-5 presents the range minimum annual storages and groundwater pumped for the two alternatives. The figure suggests that with 2040 demands and the impacts of climate change, the groundwater alternative would result in an average active minimum storage of 3.1 billion gallons while pumping almost 6 billion gallons of groundwater. For the

Dam 3 option, no groundwater is pumped and the average annual active minimum storage is 14 billion gallons.

PWB's ability to provide reliable water in the future under climate change must address three issues: a growing regional demand (a demand that is independent of climate change), an increase in water demand associated with climate change, and a decrease in the amount of water available in the late spring and summer. Although regional growth is the major source of challenge, climate change exacerbates the problem. Viable solutions to meeting water demands in the future must be able to address all three concerns simultaneously.

This research demonstrates that climate change will alter the basic hydrology of the Bull Run River watershed and the demands of the PWB and that these impacts will result in a decrease in the system safe yield. As noted in the Infrastructure Master Plan, additional investments in infrastructure will be needed to meet future demands, and when these decisions are made, the impact of climate change should be included. Both alternatives evaluated meet the forecasted water demands for the year 2040. Selection of any alternative will depend on the acceptability of increased reliance on groundwater, the challenges associated with dam construction in the Bull Run basin, system costs and system sustainability. Dam 3 provides sufficient surface water storage to meets forecasted demands well beyond 2040, even in severe drought years. The groundwater alternative evaluated provides little surface water in storage during extreme droughts and would increase the ratio of groundwater to surface water and dramatically increase the average annual groundwater pumped.

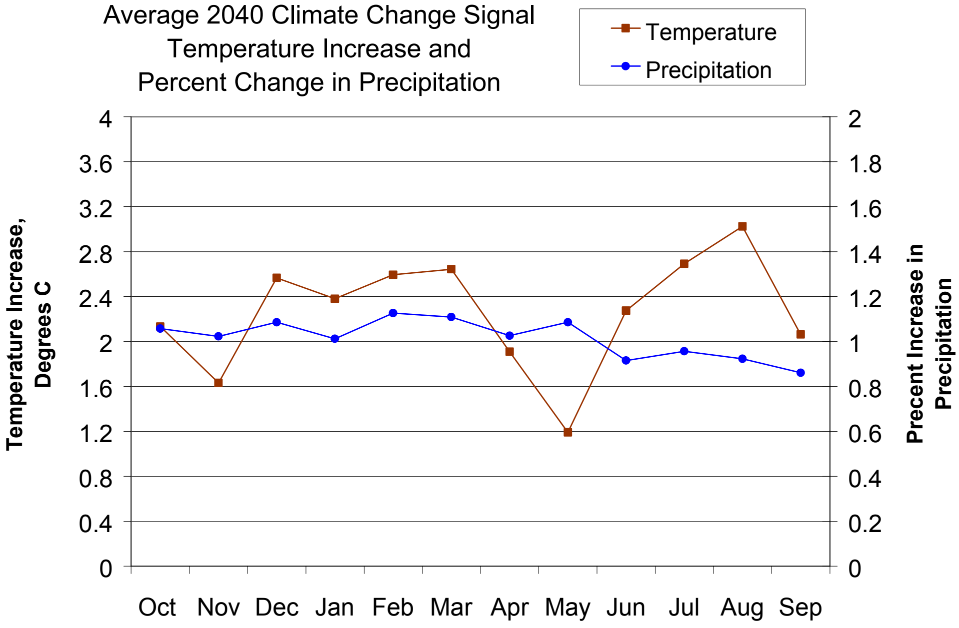

Figure ES-1. Average 2040 Climate Change Signal Temperature Increase and Percent Change in Precipitation

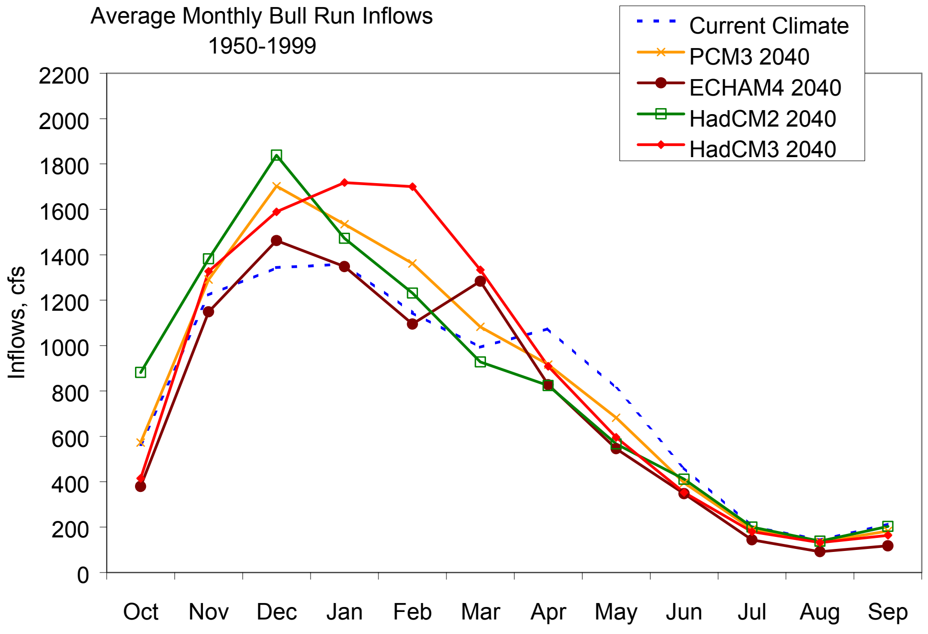

Figure ES-2. Average Monthly Flows for Current Climate and 2040 Climate Change Scenarios

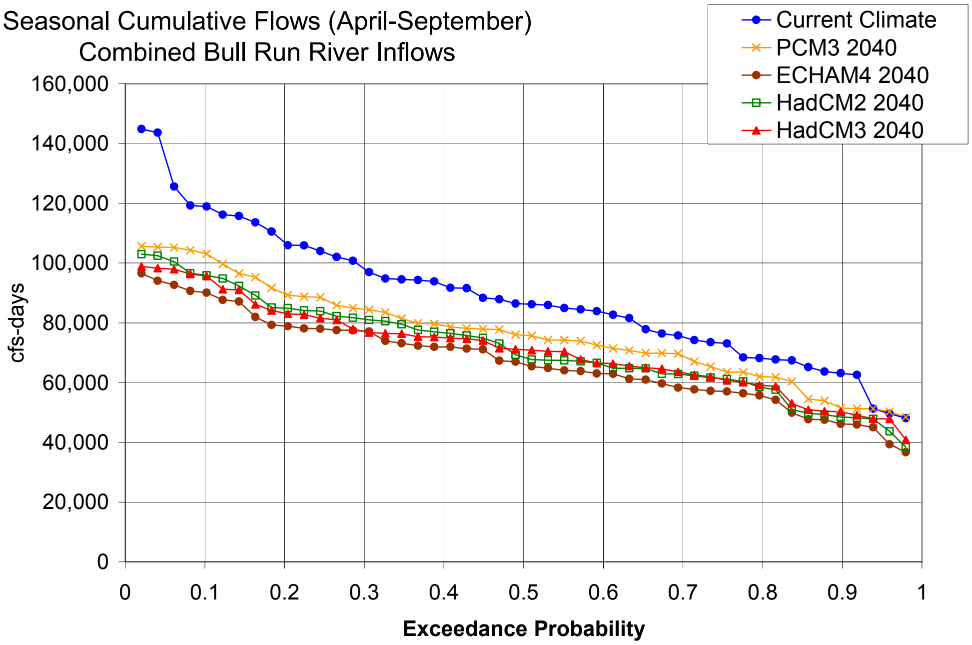

Figure ES-3. Exceedance Probability for Seasonal Cumulative Flows (April – September) for the 2040 Climate Change Scenarios

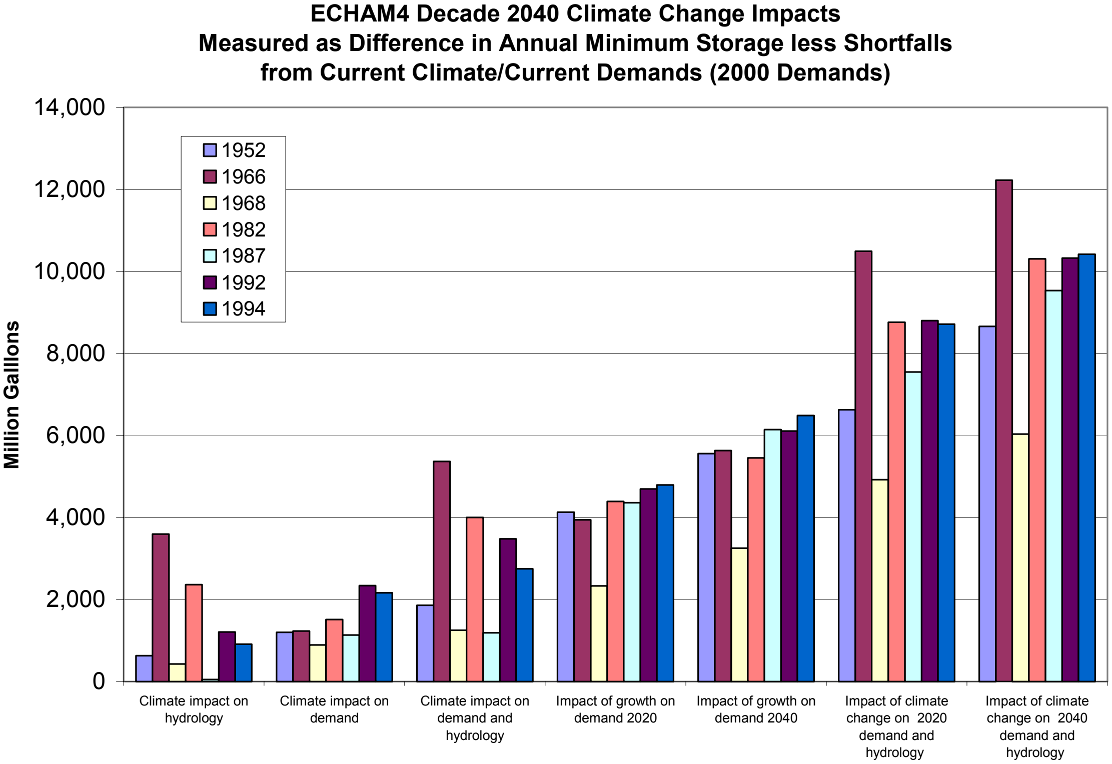

Figure ES – 4. ECHAM4 Decade 2040 Climate Change Impacts Measured as Difference in Annual Minimum Storage less Shortfalls from Current Climate/2000 Demands

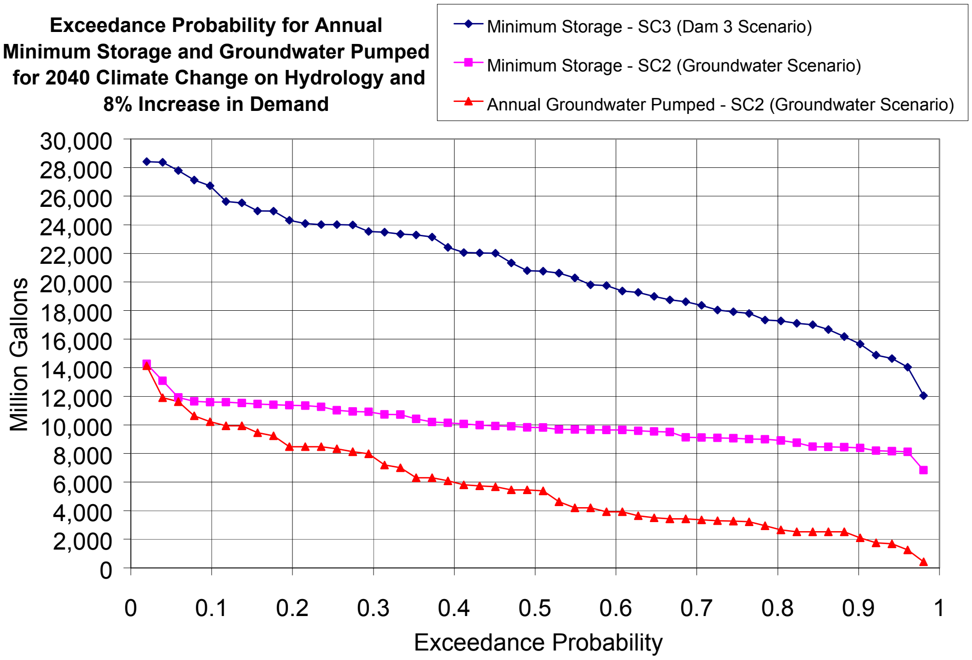

Figure ES-5. Exceedance Probability for Annual Minimum Storage and Groundwater Pumped for ECHAM4 2040 Climate Change Scenario on Hydrology and 8% Increase in Demand

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The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System

1. Introduction

This report describes the potential impacts of climate change on the hydrology of the Bull Run watershed. In addition, the study evaluates the impacts of climate change on Portland Water Bureau's (PWB) ability to provide water reliably from the Bull Run system in the future. Water supply planning has always addressed a variety of variables. The yield from surface water supplies is inextricably linked with hydrologic uncertainties. Yield calculations are typically based on historic records with the implicit assumption that climate is not changing, but with the understanding that low flow events, more extreme than those that have been recorded, could occur in the future because of climate variability.

The initial reports of the Intergovernmental Panel on Climate Change (IPCC 1996) and those that have followed (IPCC 2001) have consistently noted that our climate is in fact changing, and one of the most important impacts of climate change is on the world's water supplies. These impacts will be experienced in a variety of ways, including increased temperatures, changed precipitation, and shifts in the historic hydrologic cycle. These reports have noted that not all regions will be impacted equally, with some regions experiencing particularly negative effects, while other areas may actually benefit from climate change. Due to the limited resolution of early, large-scale, general circulation models (GCMs), the calculation of the precise impacts of climate change was left to later studies.

The impact of climate change on water supplies in the Pacific Northwest has been of interest for a number of years (Hahn et al. 2001, Lettenmaier et al. 1999, Wood et al. 1997). Pacific Northwest basins hold particular intrigue because of the interplay of two factors, rainfall and temperature. All of the major water resource systems in the Northwest rely on snowpack to provide a significant source of water in the late spring and early summer. Changes in temperature and precipitation alter the delicate interaction between the amount of precipitation that falls as either rain or snow, the eventual accumulation of snow during the winter, and temporal variability with which this snow melts and flows through the watershed.

The extent to which climate change may impact a watershed and its use are a function of several factors including the magnitude of the change in climate, the degree to which the watershed has already reached its sustainable use, and the physical setting of the watershed. Small shifts in climate (precipitation and temperature) may not result in significant changes in a watershed. However, watersheds that are already at their sustainable level of use may be negatively impacted by even minor shifts in climate. Watersheds that are located at high elevations may not be impacted by modest changes in temperature, as most of their precipitation will continue to fall as snow. Watersheds at low elevation will likewise likely be unaffected, as precipitation will continue to fall as rain. Changes in winter total precipitation may not impact water supply systems, as this water is not typically captured for later use. Changes in spring and summer precipitation may have significant impacts.

Water supply systems that rely on transient watersheds are at the greatest risk. A transient watershed receives its precipitation as both rain and snow resulting in a “two peak” hydrograph, one peak in early winter from rain fall and another peak in the spring due to snow melt. Watersheds supplying municipal water in the Pacific Northwest in particular encounter the possibility that even small changes in climate may influence the quantity and timing of runoff. Analysis of the impacts of climate change in municipal watersheds for Puget Sound, Washington reveal a change in the timing of streamflow volumes, a result of the climate change induced snow accumulation and melt (Hahn et al. 2001). The Bull Run watershed, similar in elevation and vegetation to other Western Cascade municipal watersheds, is examined here in detail to determine the range of potential impacts associated with climate change.

Climate change is, of course, only one of many concerns faced by utilities when they plan for the future. Utilities must also cope with the uncertainties associated with water demand, conservation, changing user demographics, unanticipated treatment costs, maintenance of system infrastructure, changing water quality regulations, evolving requirements of aquatic populations and other environmental concerns, and their ability to develop and maintain new water supply options.

Explicit consideration of climate change is important, however, as it may significantly alter water supply sources that have been considered "certain" in the past. Climate change can not be controlled directly by an individual utility (this will be done at a national and global level), but it is a concern that can only be planned for and carefully considered in the evaluation of source reliability. Climate change impacts on water supplies are now being studied as evidence that climate change in the 20th century is becoming more evident and our ability to understand and model its impacts is improving (IPCC 2001). It is a significant purpose of this report to place potential climate change in perspective to other planning concerns, most explicitly that of growing future water demands.

This study employs a series of loosely linked models to address potential impacts of climate change. These models simulate three aspects of process: the climate, the hydrologic cycle, and water supply system management. Outputs from climate models are used to alter past meteorologic data to capture the potential impacts of future climate. These data then serve as inputs into a hydrologic model of the Bull Run watershed. The streamflows generated by the hydrologic model become inputs to the water supply systems model.

This report describes the models that are used, the analysis process, and the results that were generated for the Bull Run system. Section 2 describes the hydrology of the Bull

Run watershed and the interaction between the basin's hydrology and the Portland Water Bureau's system of reservoirs. Section 3 discusses the models and model assumptions used in the analysis. Section 4 presents the climate change impacts that come from the General Circulation Models. Section 5 describes how climate change is modeled within the watershed. Section 6 describes the impacts of climate change on the water supply system performance. The final section summarizes the major conclusions and provides recommendations for planning and management strategies for the Bull Run system.

2. Bull Run Watershed Hydrology

The Bull Run watershed is located nearly 30 miles east of the City of Portland. The watershed contains three reservoirs: Bull Run Lake, a natural lake in the upper portion of the watershed; Reservoir 1, located fourteen miles downstream of Bull Run Lake; and Reservoir 2, located four miles downstream of Reservoir 1. The watershed experiences an average annual rainfall of 80 inches in the lower elevations and up to 180 inches at higher elevations, resulting in an average annual runoff of 300,000 acre-ft (97 billion gallons, 13 billion cubic feet) at Bull Run Headworks.

Reservoirs 1 and 2 (Figure 1) have a combined capacity of 50,000 acre-ft (16.3 billion gallons) of which 31,000 acre-ft (10.2 billion gallons) is active storage and 20,000 acre-ft (6.5 billion gallons) is dead storage due to natural sediments in the lower portions of the reservoirs. Bull Run Lake, used intermittently during times of drought, has a capacity of 1841 acre-ft (0.6 billion gallons). Approximately 10% of the average runoff is captured as usable storage. The ratio of runoff to active storage is large and the reservoirs historically refill multiple times every year.

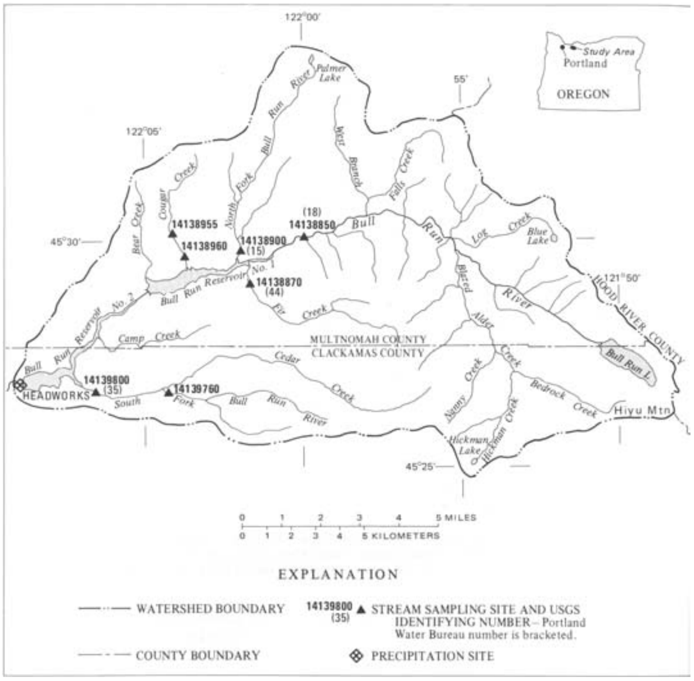


Figure 1 - Map of the Bull Run Watershed, Oregon

The basin's precipitation falls as both rain and snow. The similarity between the monthly basin hydrograph and the monthly average precipitation illustrates the strong and immediate influence of rain on streamflow. As Figure 2 illustrates, the monthly average streamflow mimics monthly average precipitation almost precisely. The months of April, May and August are the exception. In April and May snow melt contributes to streamflow. August precipitation increases, but streamflow continues to decrease, principally because of the soil deficit typical in the basin at that time.

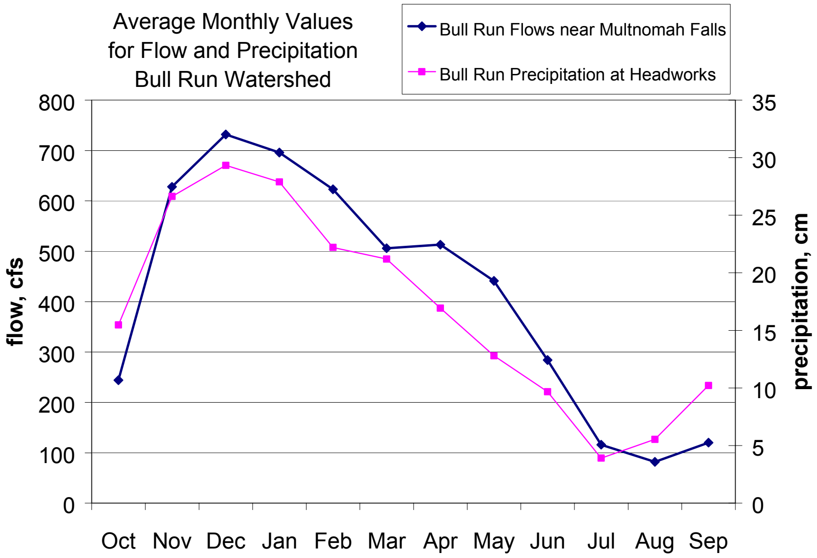


Figure 2 - Monthly Average Precipitation and Flow at Bull Run Headworks, Oregon

Not all watersheds in the Pacific Northwest demonstrate such a close correlation between monthly precipitation and monthly streamflow. Snowmelt and its timing can have a major impact on streamflow. This phenomenon is most clearly demonstrated by the Columbia River where late spring and summer flow are much higher than those that can be attributed to spring and summer rainfall. Such basins, where the monthly annual flow is created by snowmelt, are typically noted as snow-driven watersheds.

However, smaller watersheds can also demonstrate the influence of snow accumulation and melt. Figure 3 presents the monthly average streamflow and the monthly average precipitation for the Cedar River in Washington state at Chester Morse Lake. This site is at the same approximate elevation as the Bull Run site, but is located some 180 miles to the north. Figure 3 illustrates the impact of spring runoff, as streamflow during the spring is significantly greater than the contribution provided simply by monthly precipitation. A distinct, two-peak pattern is seen in this watershed, one created by rainfall (early winter), and a second created by rainfall and snowmelt (late spring). Such basins are typically noted as transient watersheds.

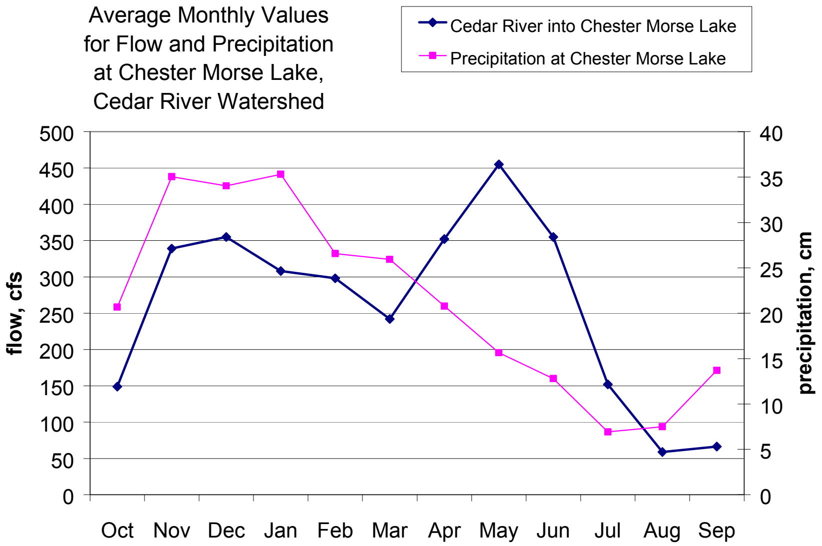


Figure 3 - Average Monthly Precipitation and Streamflow for Cedar River Watershed, Washington

The amount of snow that is captured in a watershed and the timing of its melt helps to explain the monthly watershed hydrographs. In the Bull Run watershed, snow depth has been collected consistently at the North Fork Bull Run Snotel site (#22D02S) since 1979. To estimate the quantity of water contained in a snowpack, the snow water equivalent (SWE) is calculated. A SWE measurement is based on the weight of snow and accounts for the variability in snow density. The average monthly values for SWE in the Bull Run watershed are shown in Figure 4. As indicated, about three-quarters of the maximum snowpack melts by May 1 and the remainder by June 1. The significant drop in SWE from April to May represents the majority of the spring snowmelt. This melt is also represented as the smaller April peak of streamflow in the monthly averages hydrograph in Figure 2.

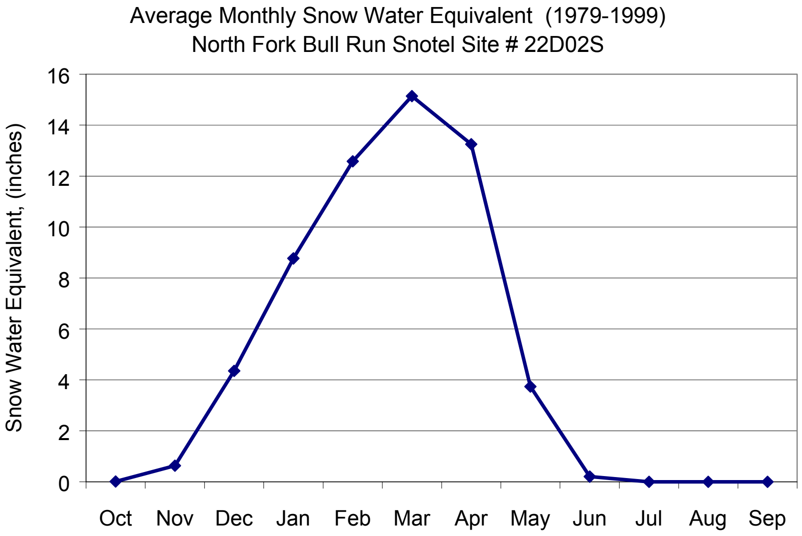


Figure 4 - Average Monthly Snow Water Equivalent for North Fork Bull Run Snotel Site

The snow melt period impacts the management of reservoirs and demand. In the Bull Run system, for the existing reservoir operating rules and current climate, the reservoirs remain full and spilling until approximately June 24th in 44 of the 49 years evaluated in this study. Figure 5 through Figure 11 illustrate the snow water equivalent (for those years after 1979) and reservoir storage in the years 1952 (large impact of climate change), 1966 (large impact of climate change), 1968 (small impact of climate change), 1982 (a typical year), 1987 (a drought year in which fall rainfalls returned late), 1992 (a drought year in which the spring snowpack was very low) and 1994 (the 1 in 10 drought event). In 1982 and 1987, snowpack refilled the system and the system had an extended period of spilling after the snowpack dissipated.

The annual cumulative precipitation and the average monthly temperature are shown for each of the years as well (Figure 12 - Figure 18). These specific years will be used to illustrate the impacts of climate change later in the report.

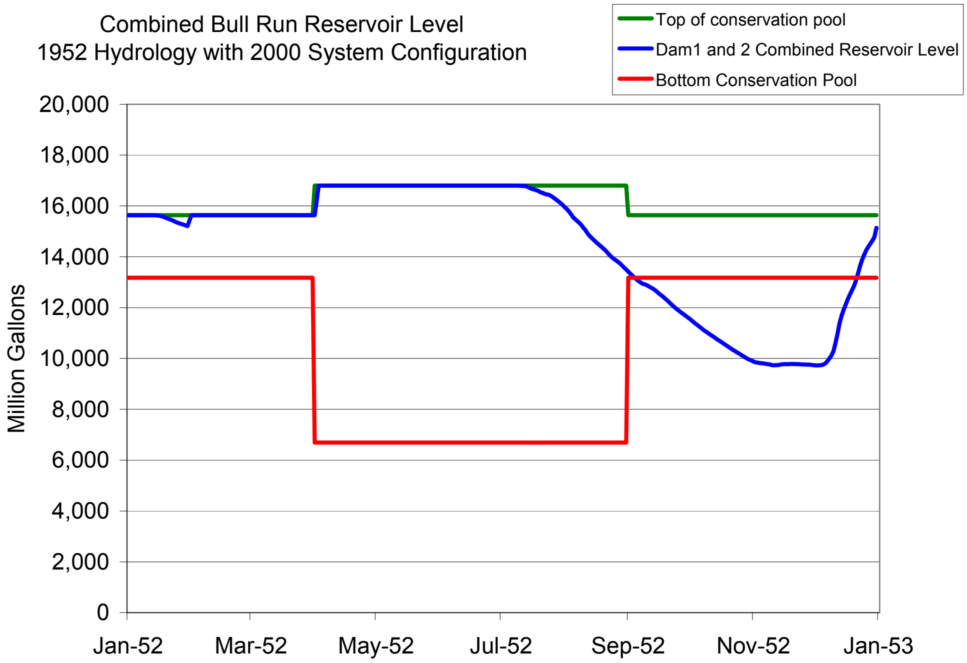


Figure 5 - Combined Bull Run Reservoir Volumes and Rule Curves for 1952 as modeled by the STM

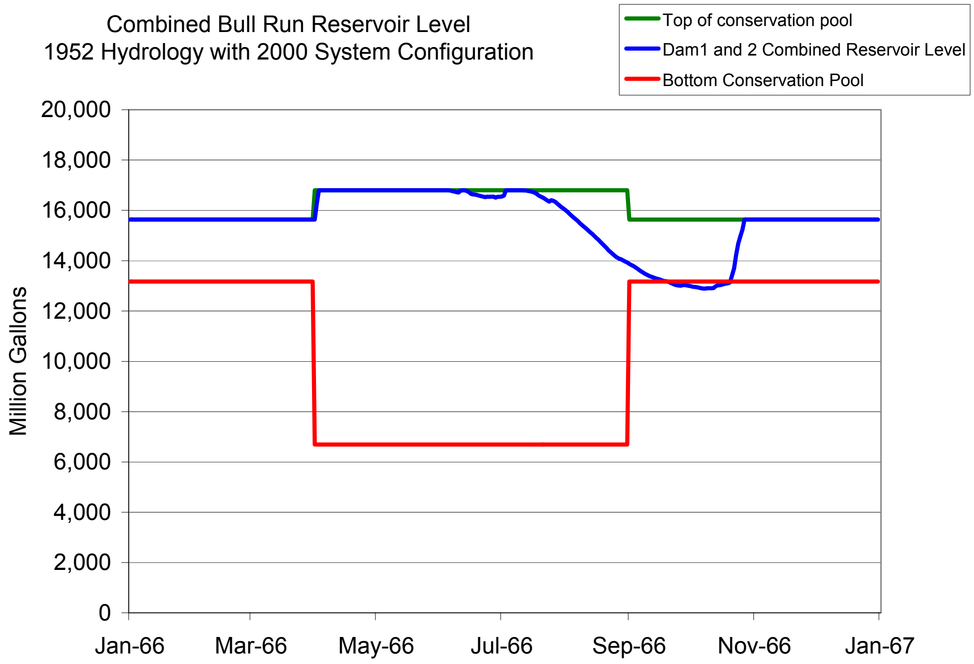


Figure 6 - Combined Bull Run Reservoir Volumes and Rule Curves for 1966 as modeled by the STM.

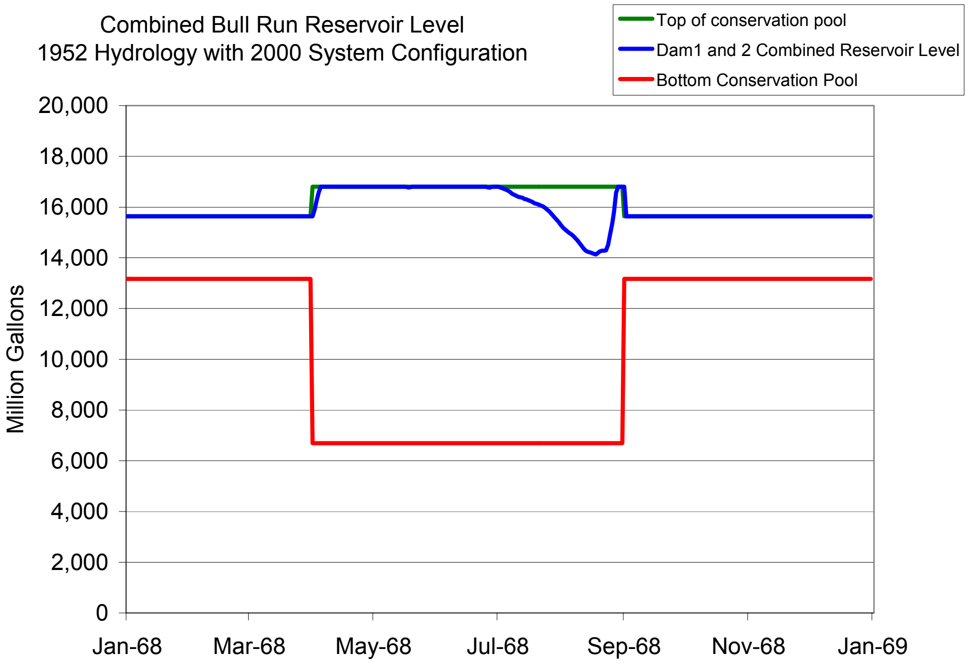


Figure 7 - Combined Bull Run Reservoir Volumes and Rule Curves for 1968 as modeled by the STM.

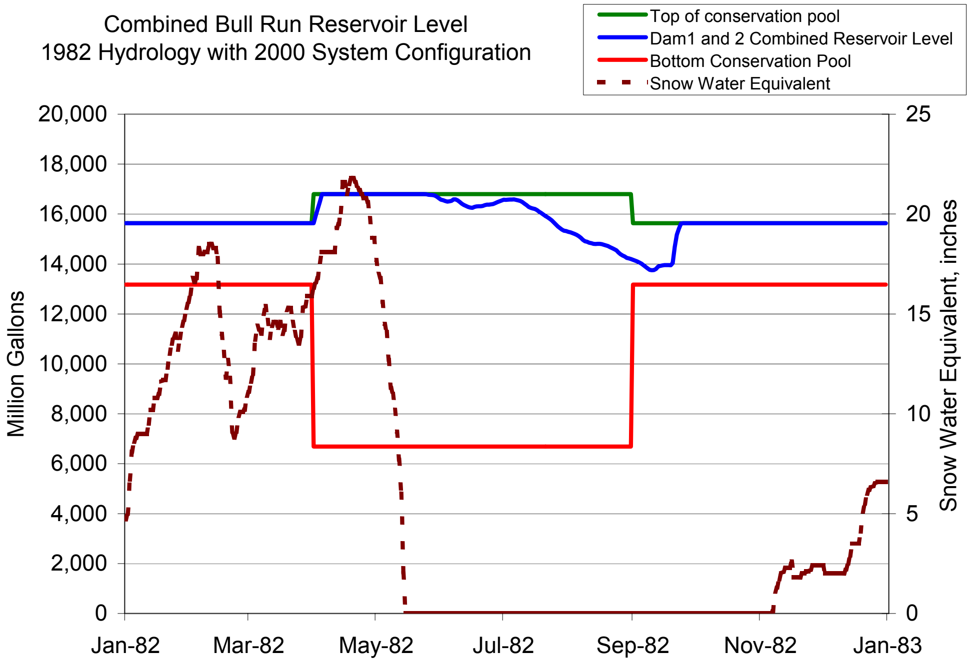


Figure 8 - Combined Bull Run Reservoir Volumes and Rule Curves and Basin Snow Water Equivalent for 1982 as modeled by the STM

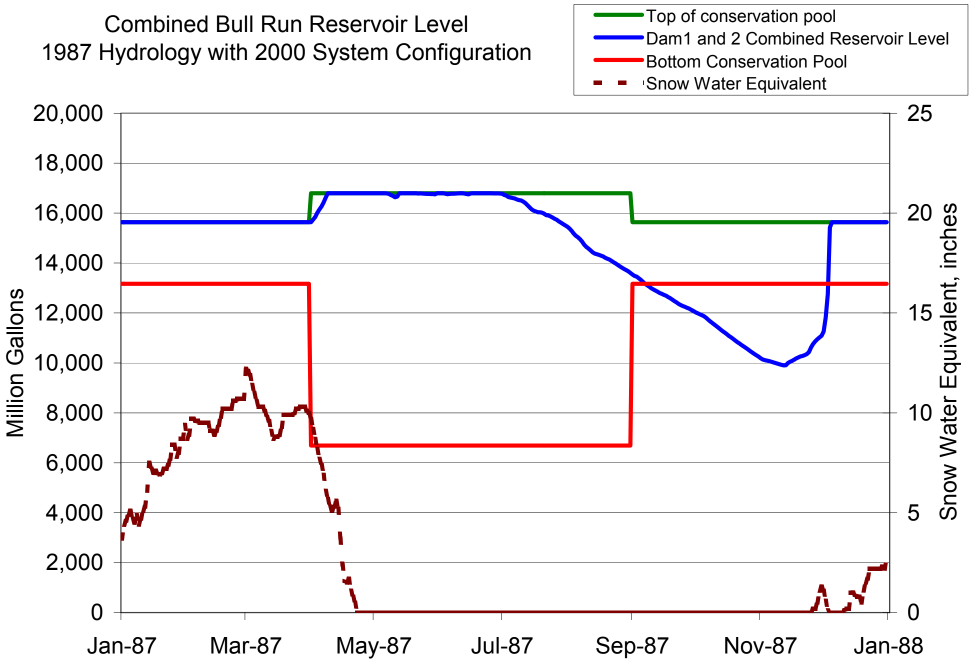


Figure 9 - Combined Bull Run Reservoir Volumes and Rule Curves and Basin Snow Water Equivalent for 1987 as modeled by the STM

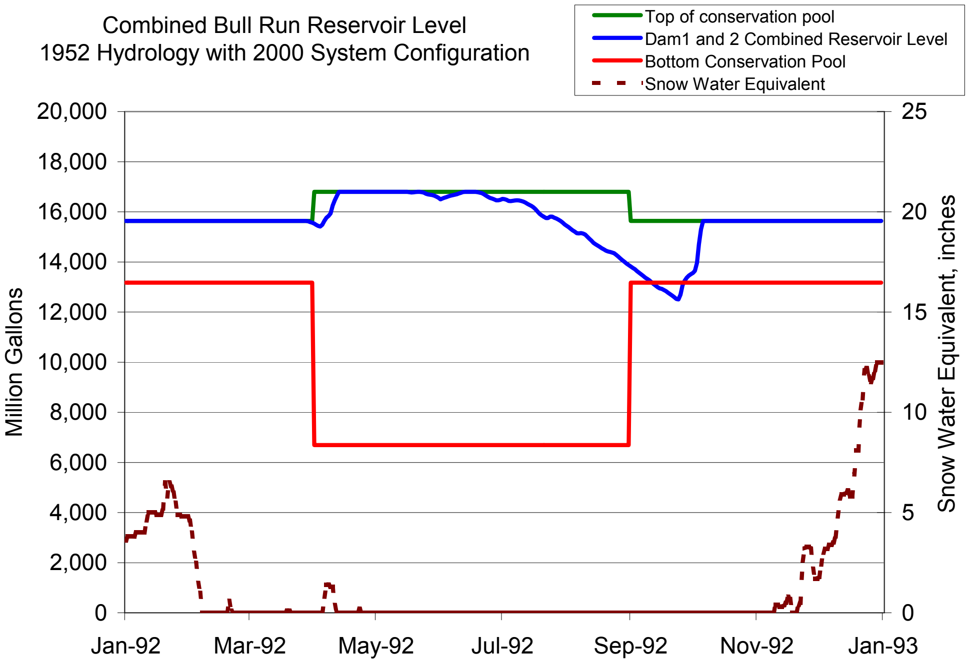


Figure 10 - Combined Bull Run Reservoir Volumes and Rule Curves and Basin Snow Water Equivalent for 1992 as modeled by the STM

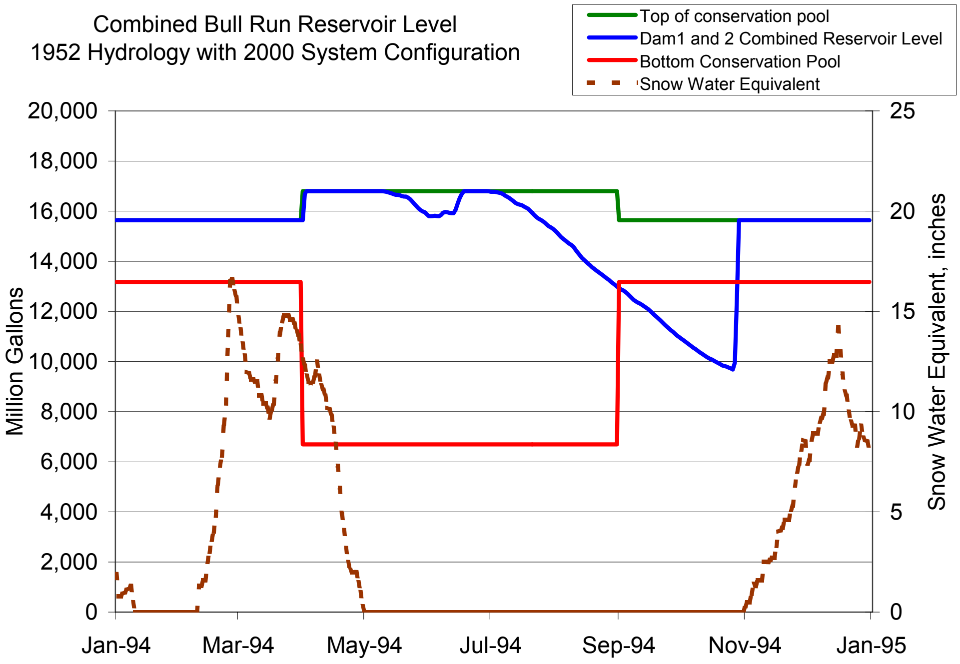


Figure 11 - Combined Bull Run Reservoir Volumes and Rule Curves and Basin Snow Water Equivalent for 1994 as modeled by the STM

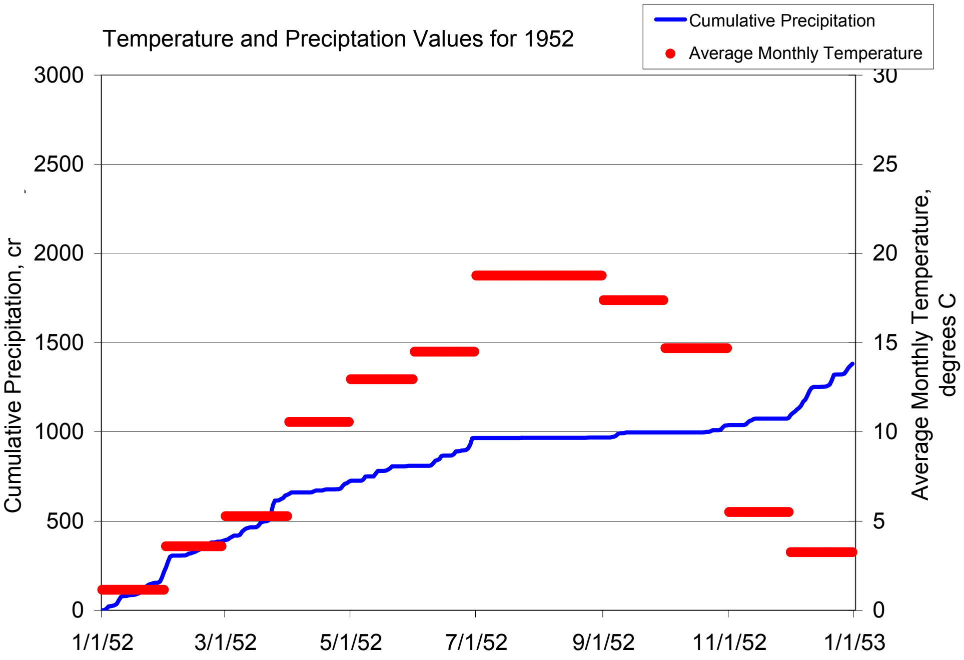


Figure 12 - Cumulative Precipitation and Average Monthly Temperature for 1952

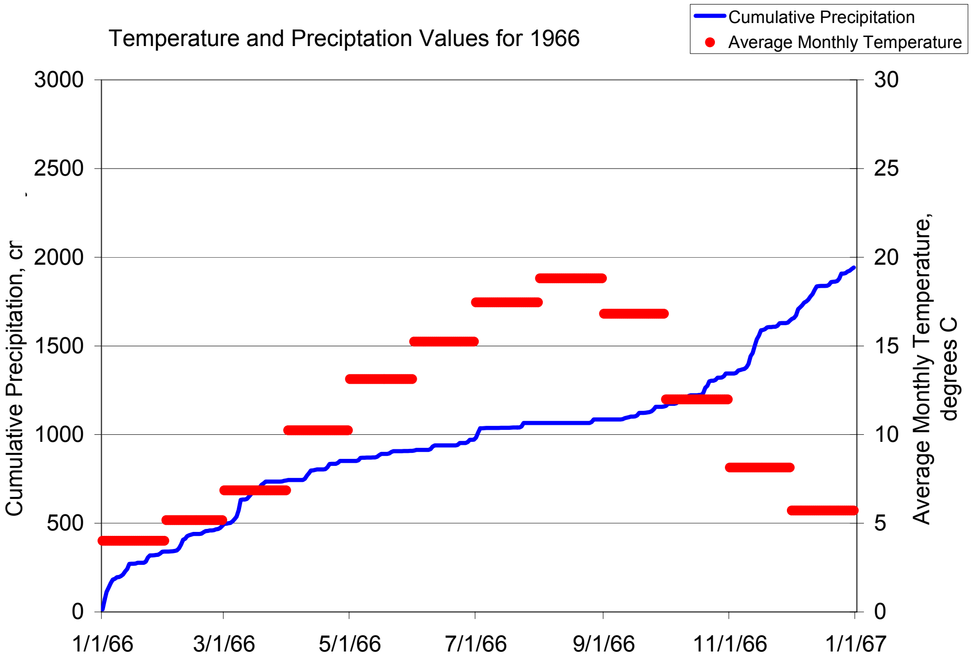


Figure 13 - Cumulative Precipitation and Average Monthly Temperature for 1966

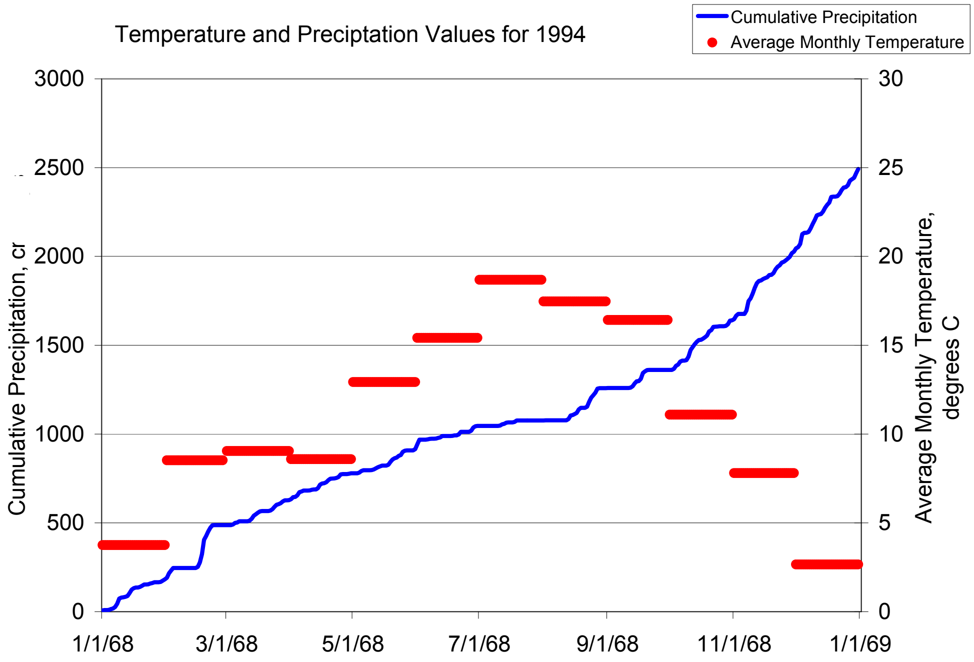


Figure 14 - Cumulative Precipitation and Average Monthly Temperature for 1968

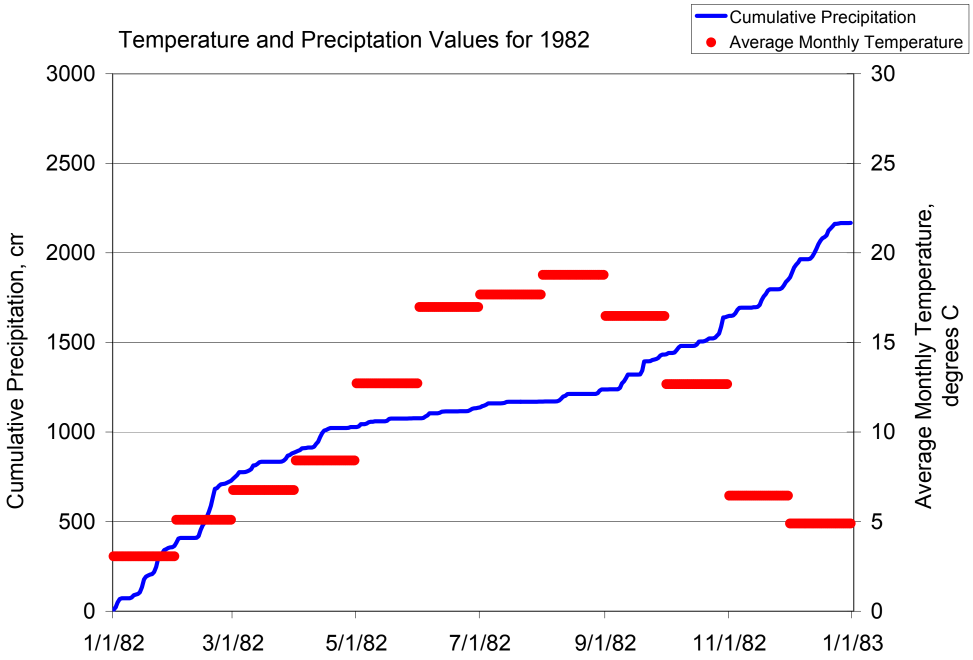


Figure 15 - Cumulative Precipitation and Average Monthly Temperature for 1982

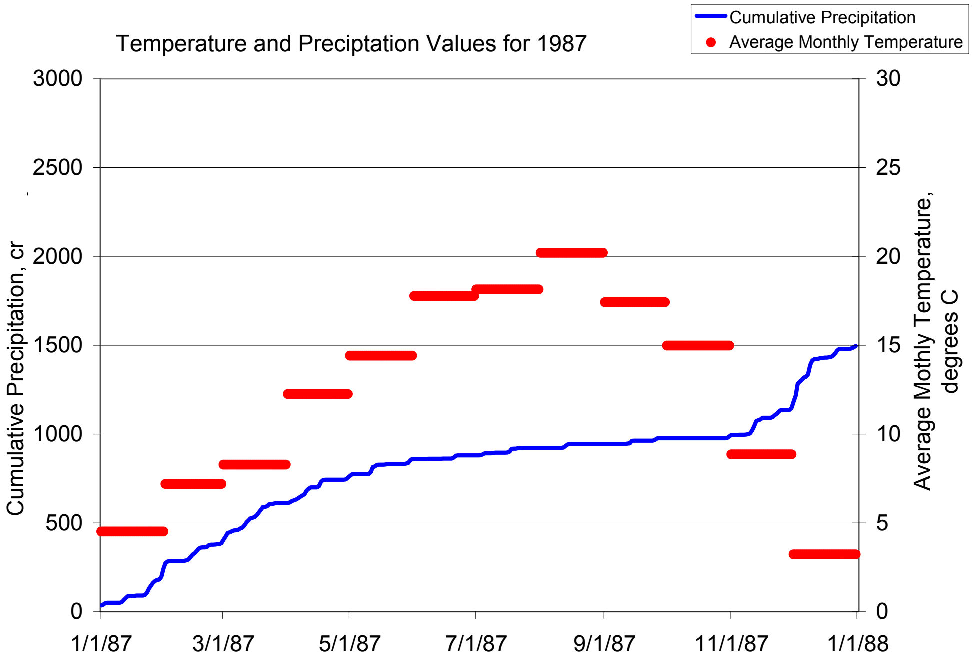


Figure 16 - Cumulative Precipitation and Average Monthly Temperature for 1987

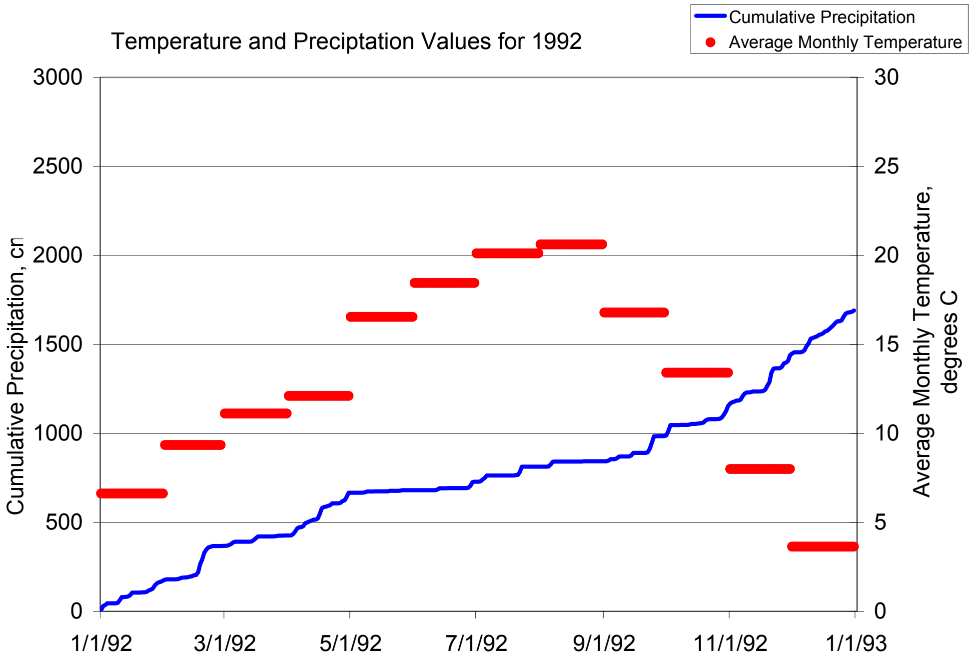


Figure 17 - Cumulative Precipitation and Average Monthly Temperature for 1992

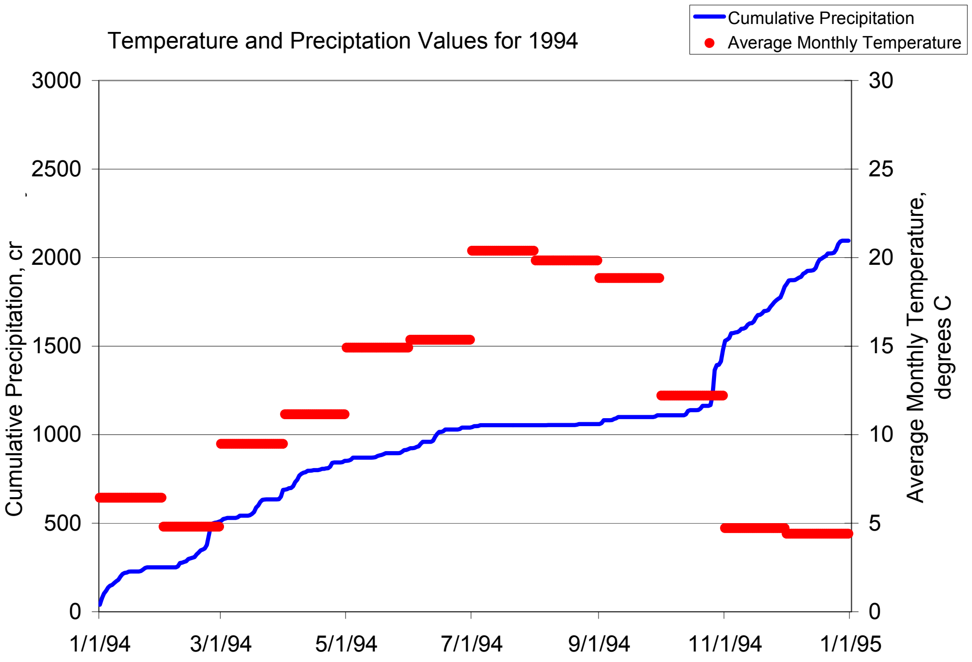


Figure 18 - Cumulative Precipitation and Average Monthly Temperature for1994

3. Models

As noted previously, three types of models were used in this study: climate models, a watershed model, and a water supply system management model. The level of direct involvement of the researchers with these models varied. The researchers did not generate the results presented from the GCMs; rather, they used published results from these models that are made available to the research community. These results represent forecasts of climate change based on specific assumptions about the production of "greenhouse" gases that have been deemed appropriate by the climate change research community. These greenhouse gas scenarios are believed to be the most scientifically defendable climate change scenarios available (IPCC 2001). The most significant role the authors played in the manipulation of these data was to "downscale" climate outputs to an appropriate meteorological data set. The downscaling process is described in the next section.

The hydrology model used in this study was the Distributed Hydrology, Soil-Vegetation Model (DHSVM). This model is a distributed model, meaning that the watershed is divided into a series of small areas (pixels that are 150 meters square) and each area and its impact on other areas is modeled explicitly. This model can be considered a "rainfall/runoff" model, although the modeling of snow is an important feature of the model. The researchers made use of the DHSVM framework and developed data sets specifically to represent the Bull Run system.

The water supply system management model used has been denoted as the Supply and Transmission Model (STM). This model was developed by the researchers specifically for the PWB, and it was modified to more readily accept the climate change data used in this study (Palmer et al. 2000). The linked model process is common in the area of climate change impacts assessment (Hamlet and Lettenmaier 1999, Wood et al. 1997, Kirshen and Fennesey 1995). Figure 19 illustrates the linking process.

Each of these models is described in detail in the following subsections.

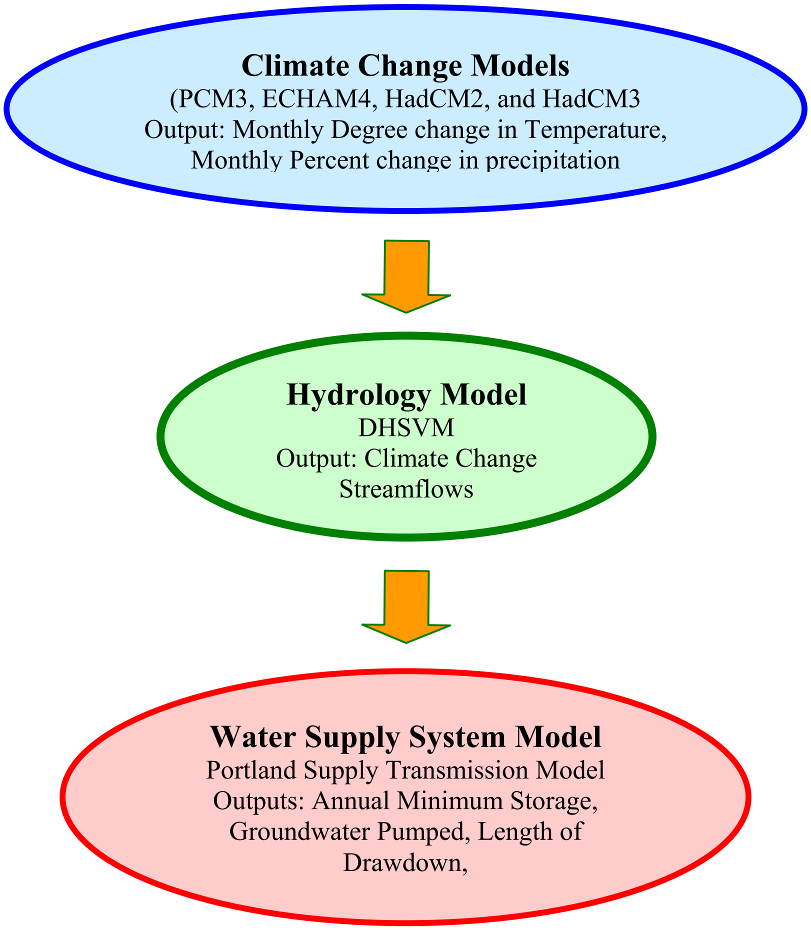


Figure 19 - Schema of Linked Models used for Assessing Climate Change Impacts

3.1. General Circulation Models

The four General Circulation Models used in this study are the Department of Energy's Parallel Climate Model (PCM), the Max Planck Institute's ECHAM model and the Hadley Centre's HadCM2 and HadCM3 models. These models incorporate a one percent increase in carbon dioxide per year. They report climate information for the years 2025 and 2045, which are assumed to be an average for the 2020 and the 2040 decades.

The Parallel Climate model was developed in 1996 by the National Center for Atmospheric Research with support from the US Army Corps of Engineer's Cold Regions Research and Engineering Lab and Los Alamos National Laboratory with funding from the US Department of Energy. It is a coupled atmosphere-ocean model with a 2.8 by 2.8 degree resolution. The results of the PCM were not included in the most recent assessment by the IPCC, but are currently being used for climate change studies throughout the western US (PCM 2001).

The Hadley Center models and the Max Plank models are included in the most recent IPCC report (IPCC 2001) and in IPCC reports of the past (IPCC 1996). The Hadley Center models, HadCM2 and HadCM3, were developed in 1994 and 1998, respectively. These models are also coupled atmospheric models with resolutions of 2.5 x 3.75 degrees. Although the HadCM3 is the successor model, the Center uses both models to produce climate change signals. The difference between the two models is primarily in the modeling of ocean layer interactions and ocean decadal variability (Hadley Center 2001). The Max Planck Institute of Meteorology model, ECHAM4, is an atmosphere only model with a resolution of 2.8 by 2.8 degrees. The ECHAM was developed in 1995 and is based on the weather forecast model of the European Centre for Medium Range Weather Forecasts (ECMWF) (Max Plank Institute 2001). There are many other atmosphere and climate models being used and developed in the research community. The climate model results used in this study are respected in the climate change community as indicated by the use of the results by the US Department of Energy and the IPCC.

The climate signals from these models are not used directly but are “downscaled,” because the spatial resolution of the models is relatively coarse. This coarseness prevents the explicit consideration of many geographic, orographic, and maritime features (landscape and vegetation, mountains, bodies of water) that directly impact expected climate effects. To "downscale" the climate information, it was translated from a multi-degree to a one-degree scale with the Symap algorithm (Shepard 1984).

The climate signals from GCMs are calculated by taking the average monthly difference of temperature and precipitation of the specific climate model control run (a run that simulates current climate) and a future climate model prediction. The temperature signal is the difference of the control and future monthly temperature averages, and the precipitation signal is the percent difference of the control and future monthly precipitation averages (Hamlet and Lettenmaier 1999).

As noted previously, the principal outputs from the climate change scenarios used in the watershed model are temperature and precipitation. Average monthly differences in temperature and precipitation in the GCMs at the year 2000 and the GCMs at future years (2020 and 2040) are used to determine average monthly shifts due to climate change. These shifts or "deltas" are then applied to the historic data that are used as inputs into the watershed model. In any given year the impacts of climate change are created by using the basic historic temperature and precipitation data shifted by the appropriate delta value. Again, it is important to note, however, that simple changes in temperature and precipitation can significantly alter the amount of precipitation, the proportion of rain to snow, and the timing when snowpack in a watershed melts. These changes form the foundation of the impacts that will be investigated in this report.

3.2. Distributed Hydrology, Soil-Vegetation Model

The hydrology model used in this analysis, Distributed Hydrology, Soil-Vegetation Model (DHSVM), produces daily streamflow values that reflect the climate change signal. DHSVM is a physically based hydrology model that characterizes a watershed as a multi-layered 150 m grid. Each pixel in the grid is characterized by several physically based data layers, including the soil and vegetation type, soil depth, vegetation height, and surface elevation and slope (Figure 20). The model simulates hydrologic processes with meteorologic data (temperature and precipitation) and the physical data layers that are unique to the watershed. The runoff in the simulation is transferred from cell to cell and accumulates into in a streamflow network layer.

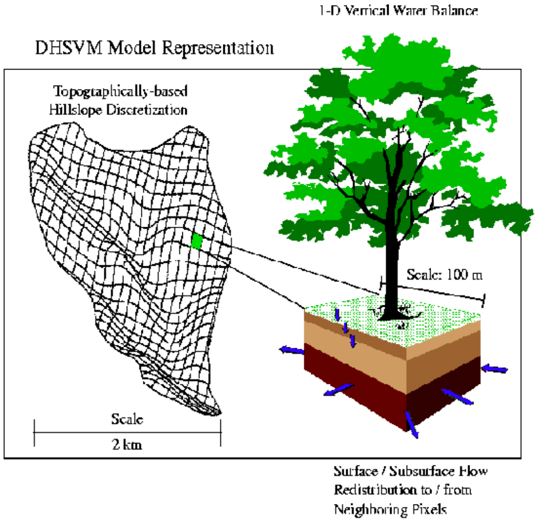


Figure 20 - Schematic of the grid and layer system of the Distributed Hydrology, Soil-Vegetation Model

The small grid size of DHSVM enables the model to effectively simulate small-scale catchments with complex topography. The model, developed at the University of Washington and Battelle Memorial Institute, has been used most extensively and successfully in the tree lined watersheds of the Pacific Northwest (Wigmosta 1994, Bowling 1997, Van Shaar 2000, Storck 2000). It is currently being used at the University of Washington to generate short-term streamflow and snowpack forecasts for basins along the western slopes of the Cascade Mountain range (http://hydromet.atmos.washington.edu/).

Each DHSVM application is based on a series of data sets and model parameters that are unique to a watershed. The data sets represent the general physical nature of the basin (elevation, soil type, precipitation, vegetation) and the parameters represent more detailed characteristics of interactions (roughness of snow, leaf area index, etc.) among the physical components of the basin. The application of the DHSVM to the Bull Run watershed included gathering spatial data sets that describe the basin's physical nature, collecting meteorologic data sets that describe the precipitation and temperature of the basin for an extended time period, and calibrating the model so that the simulated streamflows represent the observed streamflows.

The calibration of DHSVM for the Bull Run watershed is briefly outlined below with the final calibration results. The entire calibration process is detailed in Appendix A in a series of progress memorandums from the University of Washington to the Portland Water Bureau.

The DHSVM application to the Bull Run was calibrated in three stages: 1) an Initial Calibration, 2) a Data Set Driven Calibration and 3) Parameter Driven Calibration. This three-stage process is typical in calibrating physical models. It is important to first establish that the basic model is appropriate, apply specific data for a basin, and then modify parameter values to obtain a best fit. A fourth calibration effort is shown in this report and is the result of adjusting the monthly value for the temperature lapse rate. The improvement of the final calibration is shown in the annual hydrograph, Figure 21.

The DHSVM application of the Bull Run watershed has been calibrated by a visual inspection of an annual hydrograph and mean absolute percent error (MAPE) values comparing observed and modeled flows. The annual hydrograph and MAPE values of Final Calibration I and Final Calibration II are shown in Figure 21 and Table 1, respectively.

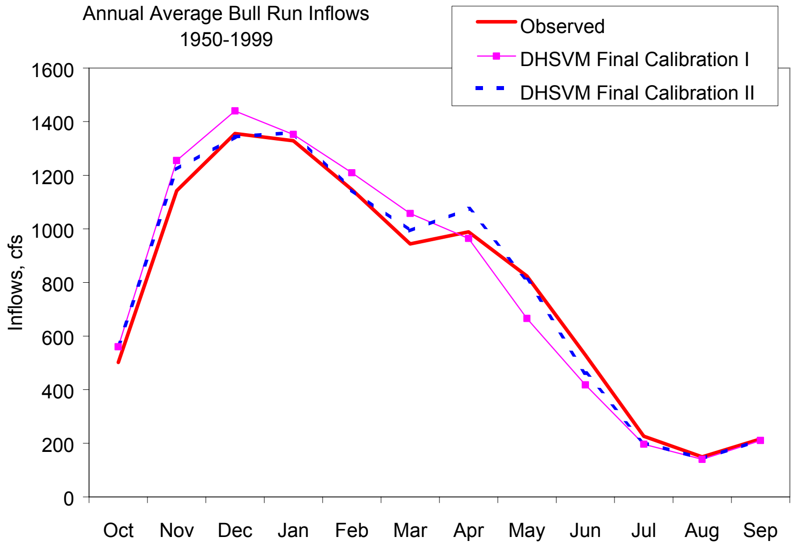


Figure 21 - Average Monthly Flows for Observed Record and DHSVM Simulated

Table 1 - Mean Absolute Percent Error values for calibration comparison between DHSVM simulated and observed average monthly flows.

Mean Absolute Percent Error	Final Calibration I	Final Calibration II
Daily (1950-1999)	33.69%	30.97%
Daily (May - November, 1950-1999)	31.44%	30.47%
Daily (May - November, 1982, 1987, 1992, 1994)	37.01%	36.02%
Monthly (1950 - 1999)	21.57%	19.41%
Monthly (May - November, 1950 - 1999)	29.46%	20.56%
Annual (1950 - 1999)	7.87%	7.71%
Annual (1982, 1987, 1992, 1994)	9.46%	8.25%

Figure 22 compares the annual cumulative flows of the observed record and the simulated flows of DHSVM, Current Climate. The DHSVM cumulative annual flows contain no consistent bias from the observed. This makes the calibration process more difficult since adjusting a parameter that gives more flow in a year that is under estimated often provides too much flow in a year that is simulated well or that is over estimated.

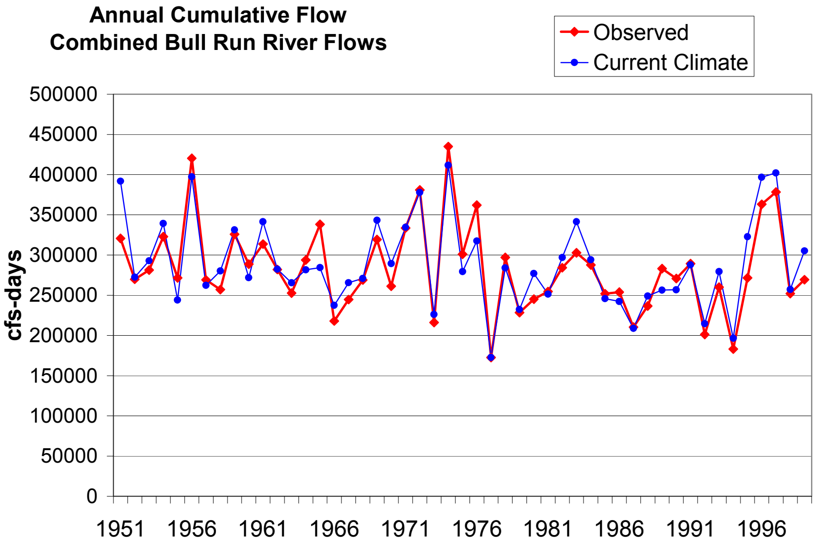


Figure 22 - Comparison of Annual Cumulative Flow between Observed flows and DHSVM simulated (Current Climate)

3.3. Supply and Transmission Model

The streamflows generated in DHSVM are used as input data for the Portland Water Bureau's Supply and Transmission Model (STM). The model was developed by the University of Washington, CH2Mhill and PWB staff over several years and has been used in the Infrastructure Master Plan. The model is currently used in the Bureau to analyze terminal storage and groundwater operations. The model can be used to evaluate future planning scenarios, such as conservation and expansion alternatives. The model is used in this study to examine the impacts of climate change on the existing system as well as two planning scenarios from the Infrastructure Master Plan. The STM and its use with the Bureau is described in the User's Guide (Palmer 2001) and in Palmer et al 2000. Figure 23 presents the Main Menu user interface of the model, illustrating the types of user information, controls and metrics contained in the model.

The STM operates at a daily time step. It simulates the flow of water throughout the water transmission system. It contains seasonally varying rule curves that control the amount of water stored in the reservoirs. It also models releases made for hydropower production, as well as for instream flows. Groundwater operations are coordinated with reservoir operations with a variety of operating alternatives that either encourage or discourage its use. The model also is designed to evaluate a large number of system expansion alternatives, together with different conservation policies. Drought management alternatives and impacts are particularly highlighted in the model. Variables, such as the length of the drawdown period, the amount of groundwater pumped during drawdown, the minimum storage during drawdown, and the water used during the drawdown, provide useful metrics to compare system alternatives. Figure 24 presents one of the output pages from the model. This page presents additional metrics for measuring drawdown during droughts.

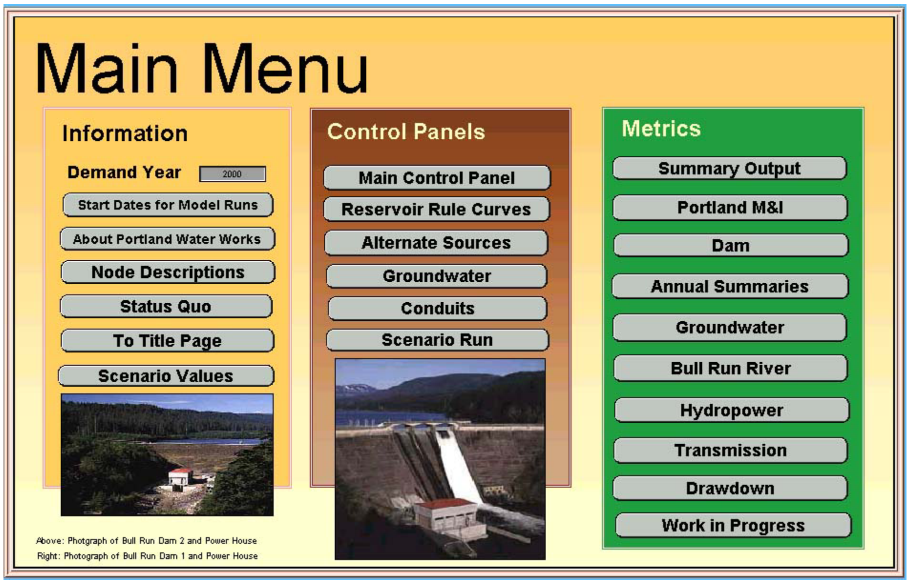
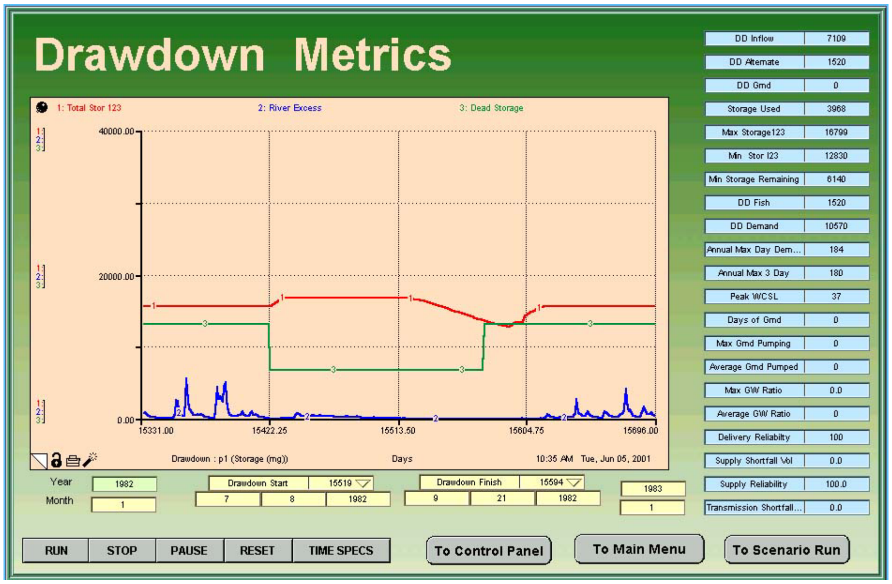


Figure 23 - User Interface of Supply and Transmission Model



Year 1982
Month 1

Drawdown Start 15519
7 8 1982

Drawdown Finish 15594
9 21 1982

1983
1

DD Inflow	7109
DD Alternate	1520
DD Grnd	0
Storage Used	3968
Max Storage123	16799
Min Stor I23	12830
Min Storage Remaining	6140
DD Fish	1520
DD Demand	10570
Annual Max Day Dem...	184
Annual Max 3 Day	180
Peak WCSL	37
Days of Grnd	0
Max Grnd Pumping	0
Average Grnd Pumped	0
Max GW Ratio	0.0
Average GW Ratio	0
Delivery Reliabilty	100
Supply Shortfall Vol	0.0
Supply Reliability	100.0
Transmission Shortfall...	0.0

Figure 24 - Drawdown Metrics Screen of the Supply Transmission Model

4. Model Results - Climate Change Impacts on the Meteorological Record

As discussed previously, the climate change signal is downscaled as a change in the temperature (°C) and a fraction change in precipitation. The monthly climate change signals for precipitation and temperature downscaled from the four GCMs are used in this study. Figure 25 to Figure 28 demonstrate that the four climate change scenarios predict warmer and wetter climates on an annual basis. One exception is the ECHAM4 2040, which predicts less precipitation in months of October, November, December, and January. The four GCMs produced significant variation in the forecasted average shift in precipitation in both 2020 and 2040. In 2020, the average precipitation increased by approximately 10% during the late summer, winter, and spring; decreased slightly in May and June; and remained unchanged in July. In 2040 precipitation was slightly more than average in October and May and less than the historic average June through September.

The change in the temperature signal also varies among the four models, but is consistently warmer. The temperature signal shows an average increase of 1.5 °C for the 2020 prediction and has higher temperatures in the summer months. The 2040 prediction follows the same trend with higher temperatures on average in the summer and an overall average annual increase of 2.0 °C. Higher temperatures in the winter months will reduce the amount of snow in the basin. The higher temperatures in the summer will likely create an increase in the summer demand.

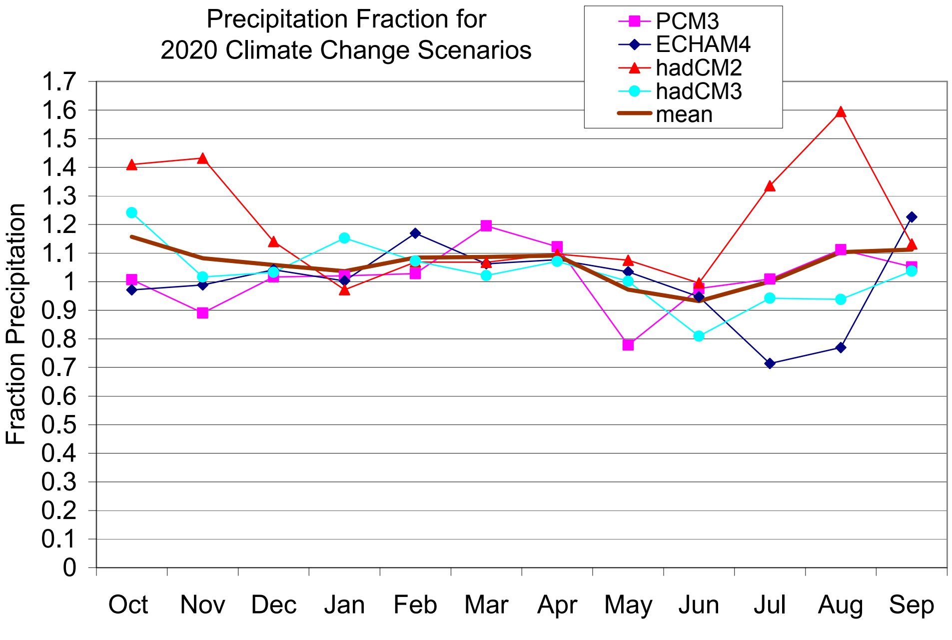


Figure 25 - Monthly Precipitation Fractions for 2020 Climate Predictions

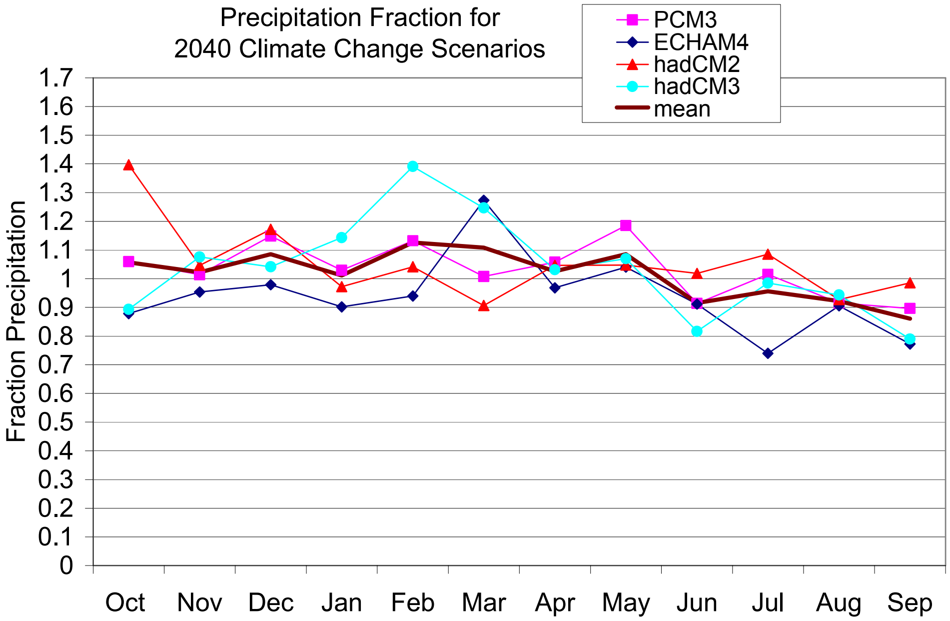


Figure 26 - Monthly Precipitation Fraction for 2040 Climate Predictions

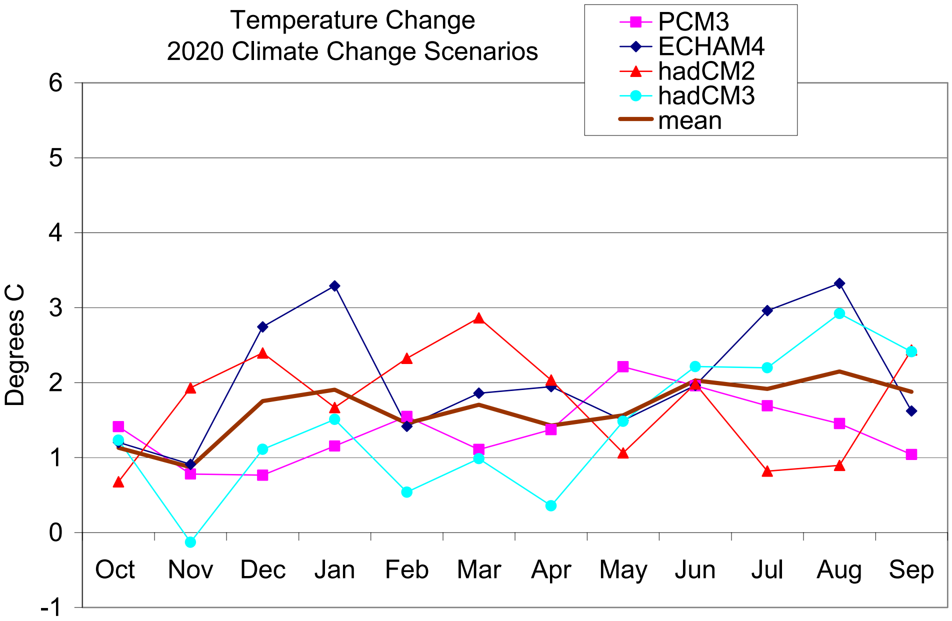


Figure 27 - Monthly Temperature Deltas for 2020 Climate Predictions

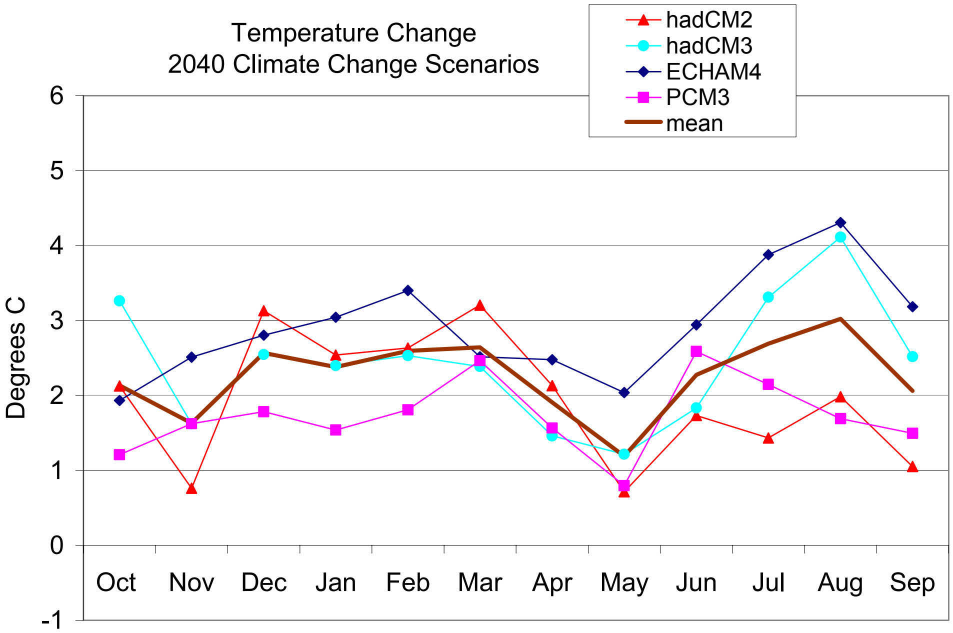


Figure 28 - Monthly Temperature Deltas for 2040 Climate Predictions

Applying the precipitation fraction and temperature changes to their appropriate months of the historical record further demonstrates the predicted climate signal. The variability among the precipitation portion of the climate change signal is apparent when applied to the actual precipitation record (Figure 29 and Figure 30). The 2020 precipitation signals vary more in the winter and the 2040 precipitation signal has a greater variance in the winter than the 2020 signal.

Although the temperatures are consistently warmer, there is variability within and between the climate decades (Figure 31 and Figure 32). In 2020, the range of temperatures is the most similar in the spring and the least similar in the winter.

The next section of the report presents the impact of the climate change signals on the hydrology of the Bull Run basin. A sensitivity analysis of the basin's response to changes in temperature and precipitation is also presented.

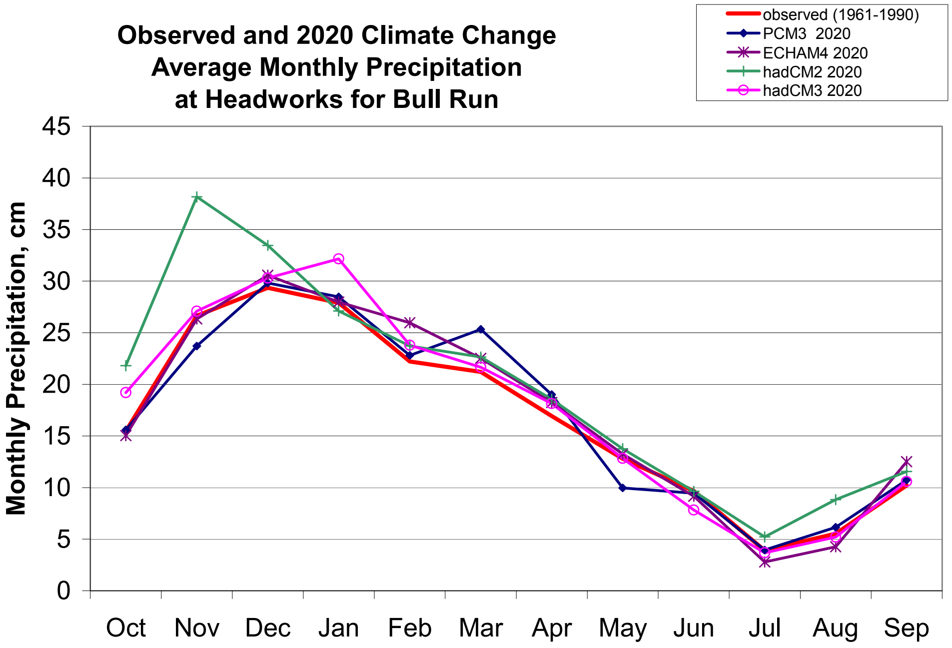


Figure 29 - Observed and 2020 Climate Change Average Monthly Precipitation at Bull Run Headworks

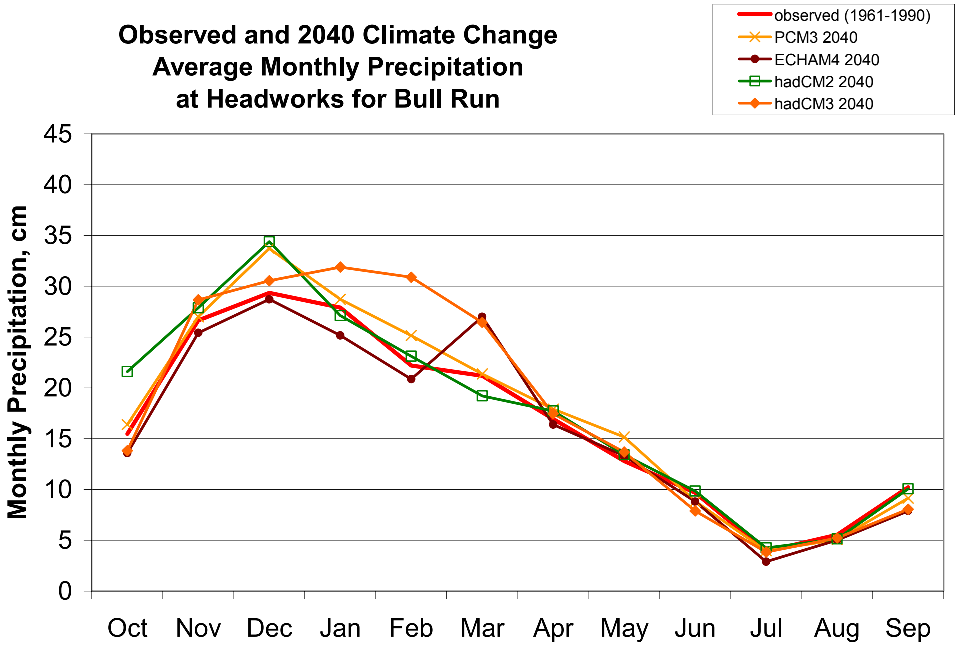


Figure 30 - Observed and 2040 Climate Change Average Monthly Precipitation at Bull Run Headworks

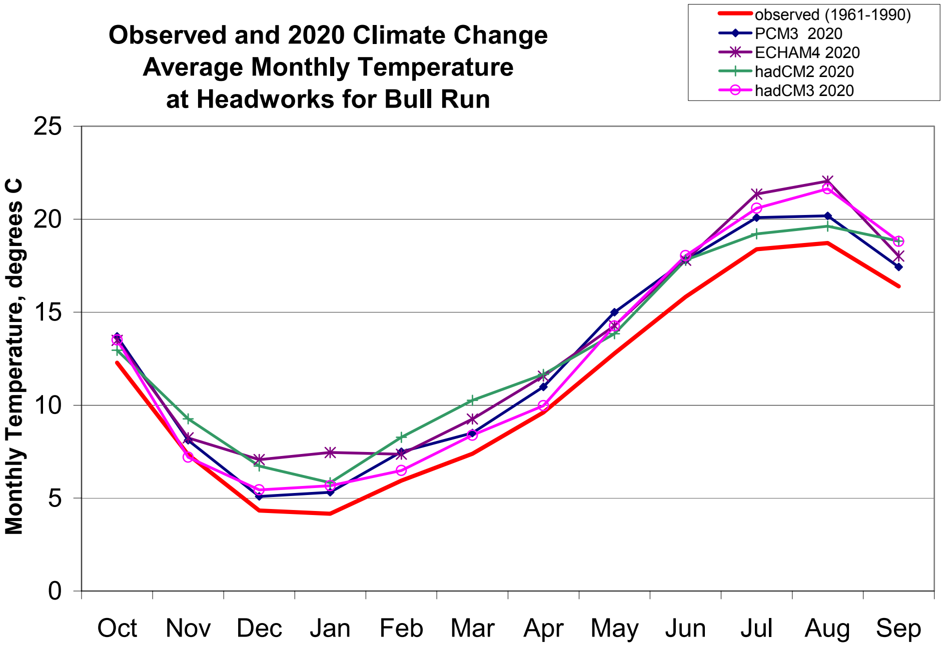


Figure 31 -Observed and 2020 Climate Change Average Monthly Temperature at Bull Run Headworks

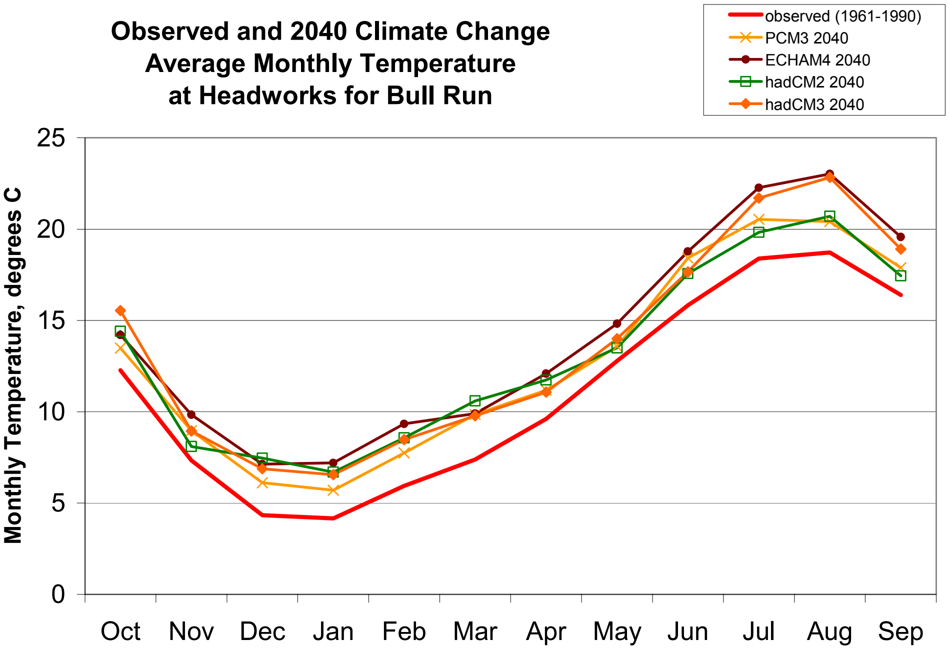


Figure 32 - Observed and 2020 Climate Change Average Temperature at Bull Run Headworks

5. Model Results – Distributed Hydrology, Soil-Vegetation Model

Having established the impacts of potential climate change on temperature and precipitation, the next step is to determine the impacts of climate change on the hydrology of the Bull Run watershed. A number of issues are important. First, will changes in temperature and precipitation associated with the 2020 and 2040 climates influence the basic hydrology of the basin? More precisely, will the volume and timing of streamflow change? Second, if there is a shift, which factors are the most important in this change: precipitation, temperature, or their joint influences on snowpack accumulation and melt? Third, how will these changes be manifested in the basin relative to water supply issues? Will climate change most likely influence annual water availability, seasonal water availability, or late summer availability?

5.1. Basin Sensitivity to Systematic Changes in Precipitation and Temperature

Before investigating the impacts of the four specific climate change signals on the Bull Run watershed hydrology, it is instructive to determine the range of hydrologic impacts that can occur by varying the historic temperature and precipitation record systematically. Figure 33 through Figure 37 present the sensitivity of the hydrology to ranges of temperature and precipitation that bracket those likely to be seen by climate change by the year 2040.

Figure 33 presents the change in monthly average annual hydrology that would occur if precipitation were increased by 10 and 20%. The increases in precipitation result in significantly higher flows for all months with the exception of the summer low precipitation months.

Figure 34 presents the change in monthly average annual hydrology that would occur if monthly temperatures were increased by 1 and 2 °C. These increased temperatures result in increased flows in the winter (December and January) and decreased snowmelt driven flows in the spring (April and June). The removal of the second runoff peak in April will be discussed further in this chapter. Figure 35 and Figure 36 couple an increase in temperature with increases of 10 and 20% in precipitation to illustrate their relative impacts. Both cases result in significantly higher streamflows in winter, as would be expected.

A final analysis was made to investigate the potential hydrologic impacts of all precipitation falling as rain (no snow). This was explored in two ways, by increasing monthly average temperatures by 4 °C and by setting the adiabatic lapse rate to 0 (that is, temperature does not increase or decrease with changes in elevation). This second approach is the effect of significantly warming the upper elevations from their actual conditions. Figure 37 suggests that these two approaches result in almost identical results. Streamflows increase in November, December, January, and February, and decrease in April, May, and June.

The systematic changes in the precipitation and temperature records provide a likely upper and lower bound to the changes that may occur with the four climate change scenarios. As indicated by these graphs, changes in total precipitation result in changes in the total volume of runoff, while changes in temperature result in changes in the timing of the runoff. Specifically, a given percentage change in precipitation results in similar increases in runoff, while increasing temperatures increase flows in the winter and decrease the flows in spring.

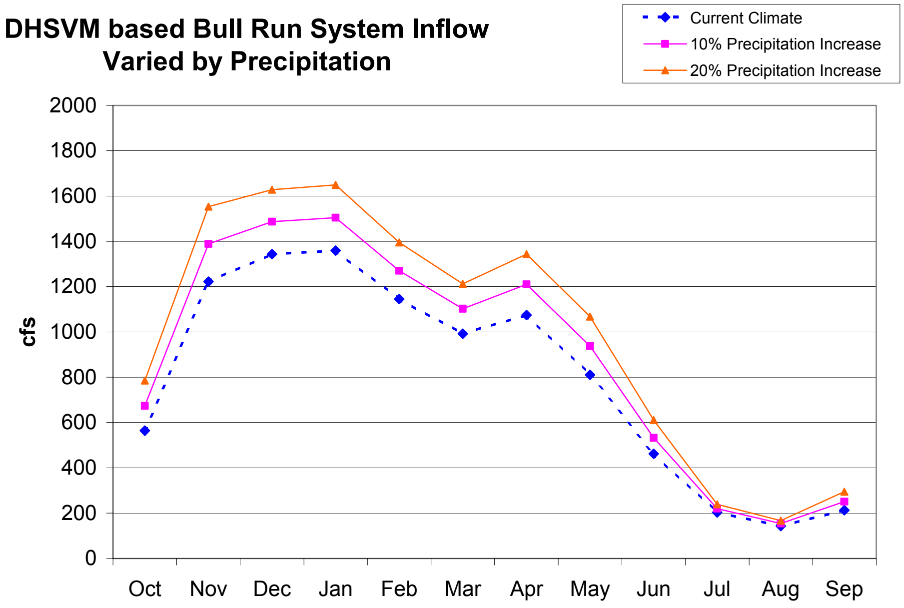


Figure 33 - DHSVM based Bul Run System Inflows Varied by Changes in Precipitation Driving Data

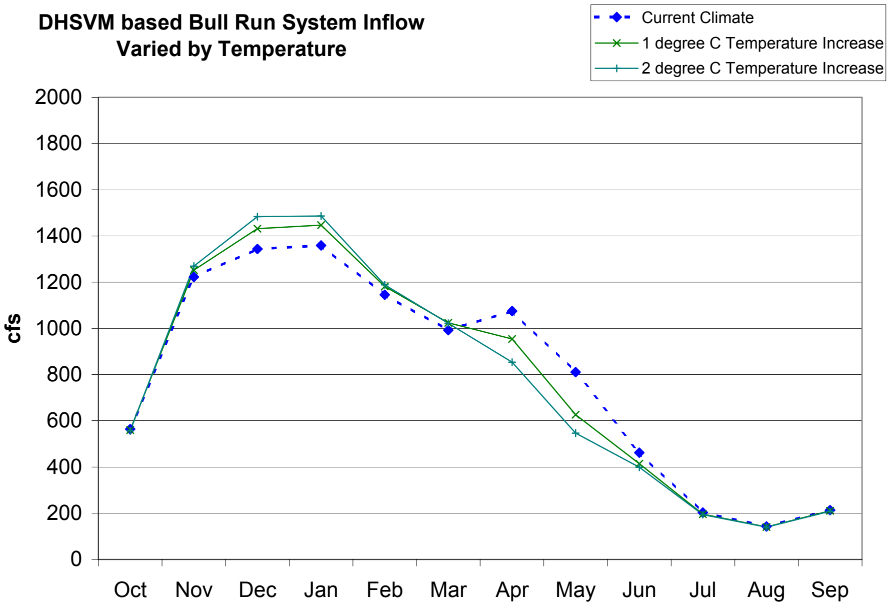


Figure 34 - DHSVM based Bull Run System Inflows Varied by Changes in Temperature Driving Data

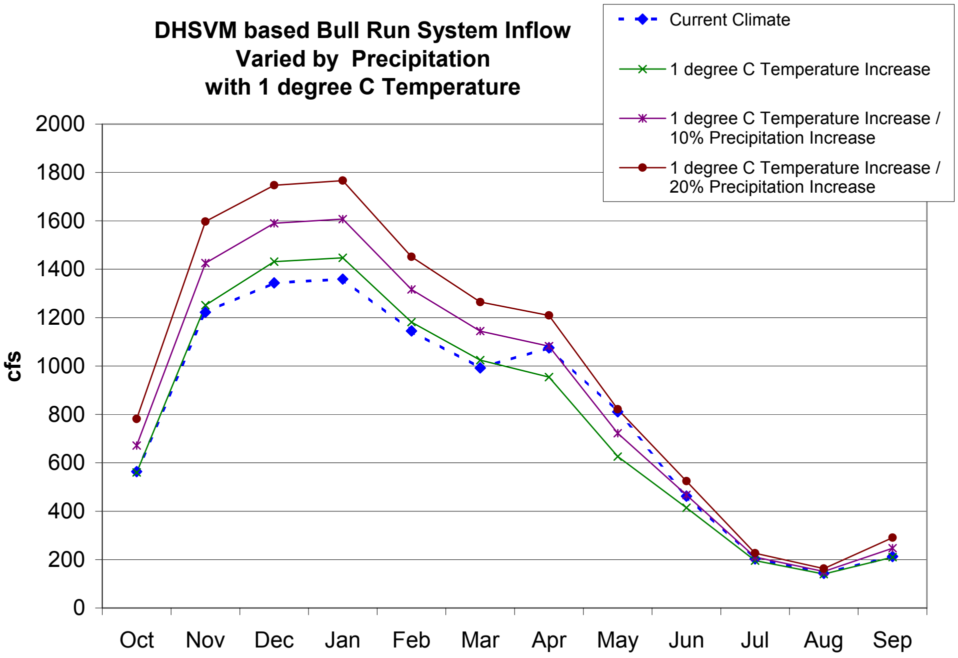


Figure 35 - DHSVM based Bull Run System Inflows Varied by Changes in Precipitation Driving Data with 1 degree C Temperature Increase

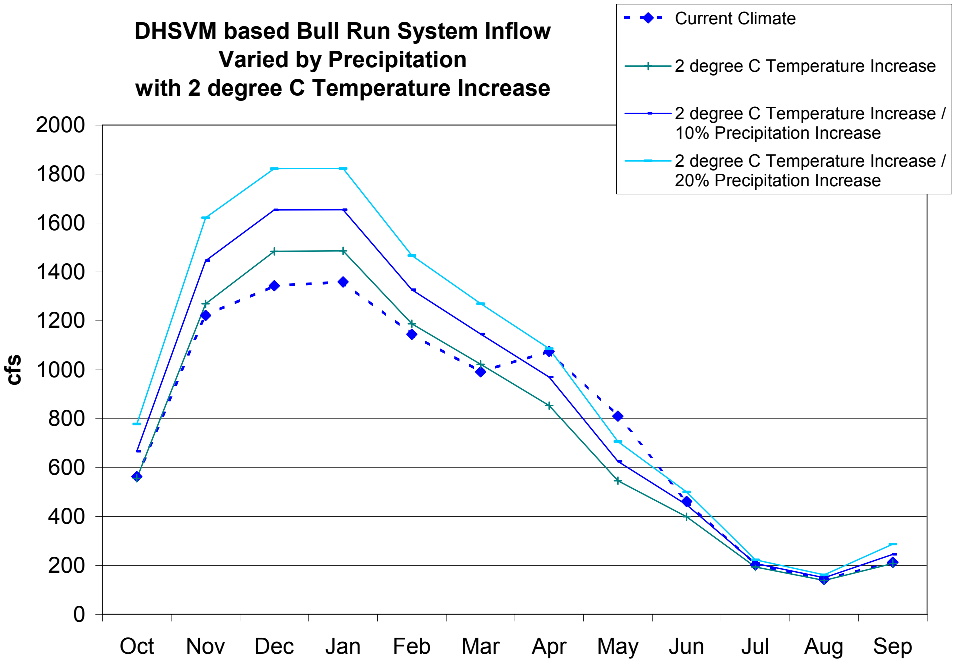


Figure 36 - DHSVM based Bull Run System Inflows Varied by Changes in Precipitation Driving Data with 2 degree C Temperature Increase

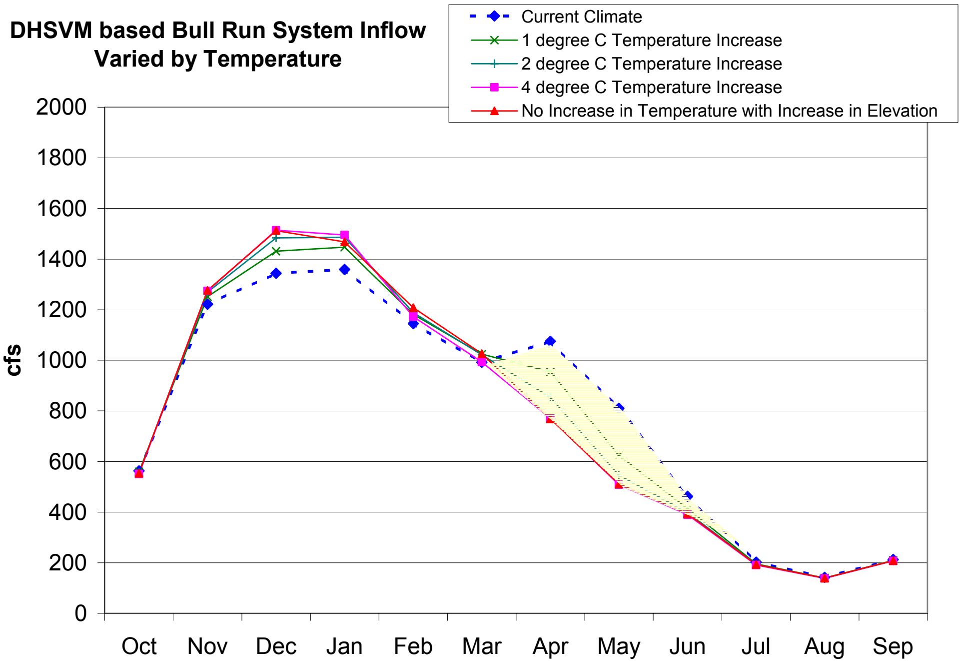


Figure 37 - DHSVM based Bull Run System Inflow Varied by Changes in Temperature Driving Date

5.2. Climate Change Signals

As noted in Section 4, variability exists between the climate change signals of the PCM3, ECHAM4, HadCM2, and HadCM3 models. It is important to recognize the relative uncertainty associated with the temperature and precipitation signals. It is widely accepted that the temperature signals from GCMs are considerably more reliable than the precipitation signal (IPCC 2001).

Figure 38 presents the average monthly hydrograph of the basin for the four 2020 climate change scenarios. The range of values for fall and winter flows is indicative of the variability of the climate change precipitation signal of the four models. The temperature portion of the signal has a relatively consistent impact, as spring flows are lower for each of the model runs. Of the four 2020 climate change runs, the PCM3 model appears to have the greatest reduction in May flows, and the HadCM2 model has a large relative impact on August-November flows.

The climate change impacts on the winter flows in 2040 are greater and more varied than those in 2020. The spring flows (April) are significantly less in the 2040 scenarios than in the 2020 scenarios. This demonstrates the impact of the warmer 2040 temperatures on spring runoff.

The increased winter precipitation and the warmer temperatures create higher winter streamflows and the lower spring time flows. This lagged effect of warmer winter temperature is similar in the four climate change signals for 2020 and 2040 (Figure 38 and Figure 39). HadCM2 2020 and the HadCM3 2040 flows are the extremes. The former causes a substantial shift in the flows to November, and the latter creates higher flows in the mid-winter (January and February). The remaining six signals are similar to one another and create higher flows in the early winter, a decrease in the spring peak and an earlier declining hydrograph in the spring.

The impacts of climate change on the basin hydrology is quantified by the season cumulative flow and presented in exceedance probability curves, Figure 40 to Figure 43. The climate change signals create greater winter flows and smaller summer flows. Extreme events also change. The cumulative winter flow for HadCM3 in 2020 is much greater than the current climate and the other climate models (Figure 40). The ECHAM4 2040 cumulative winter flows are similar to the current climate (Figure 42), where as, the ECHAM4 2040 cumulative summer flows are the lowest of the four climate models and the current climate cumulative flows (Figure 43).

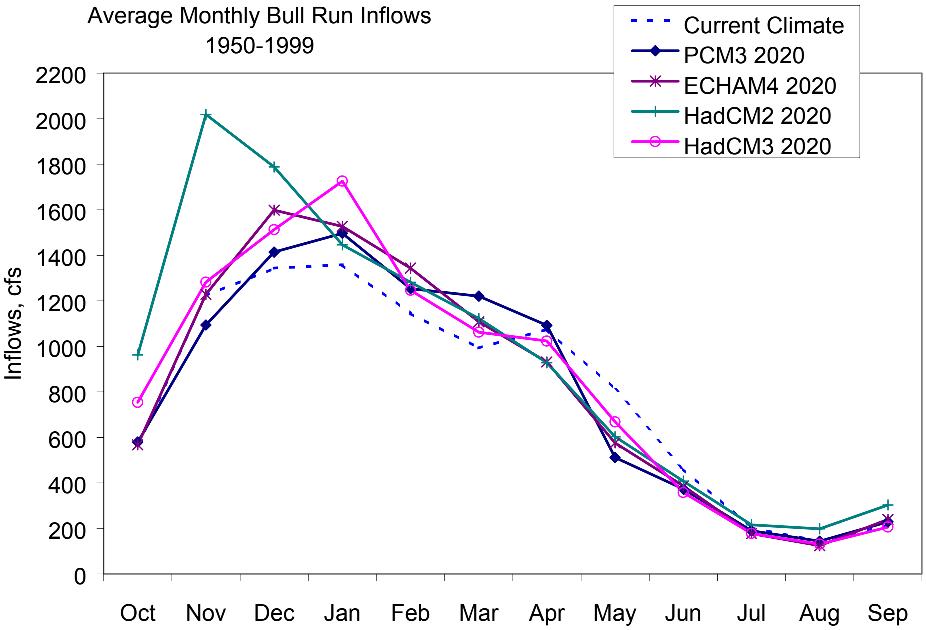


Figure 38 - Average Monthly Flows for Current Climate and 2020 Climate Change

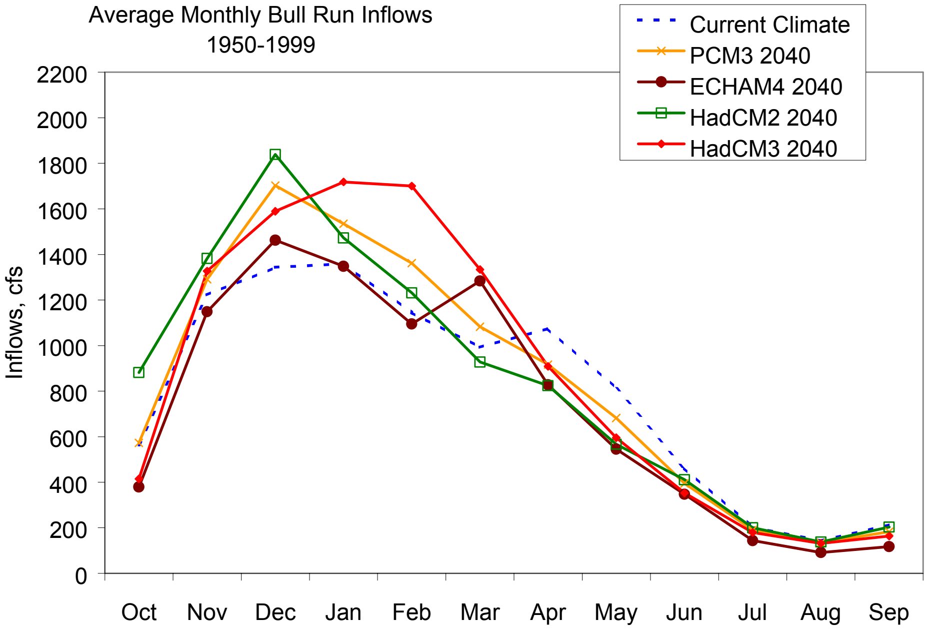


Figure 39 - Average Monthly Flow Hydrograph for Current and 2040 Climate Change

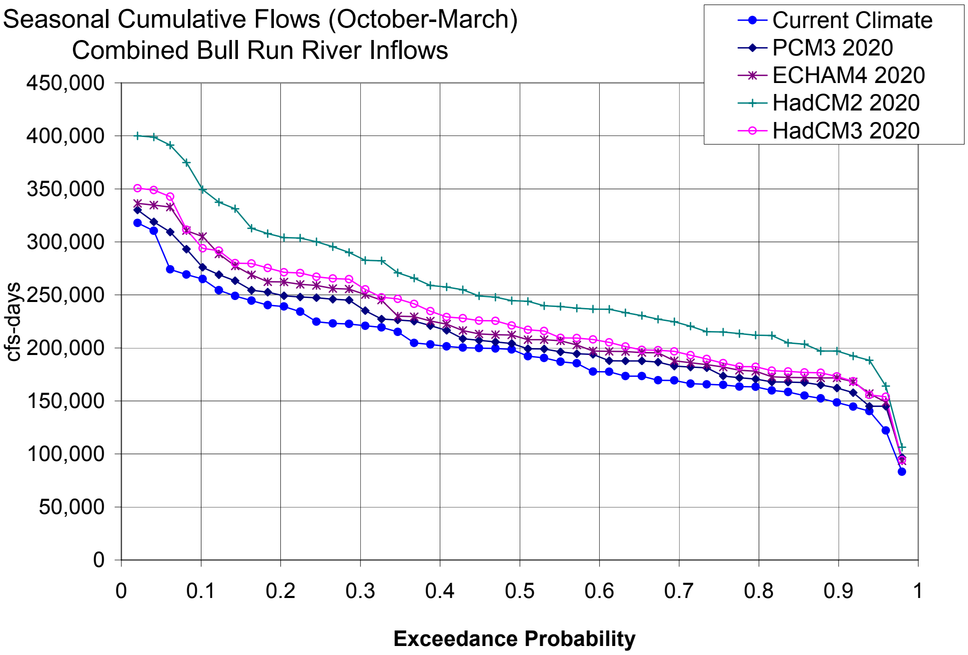


Figure 40 - Exceedance Probability for Seasonal Cumulative Flows (October-March) for the 2020 Climate Change Scenarios

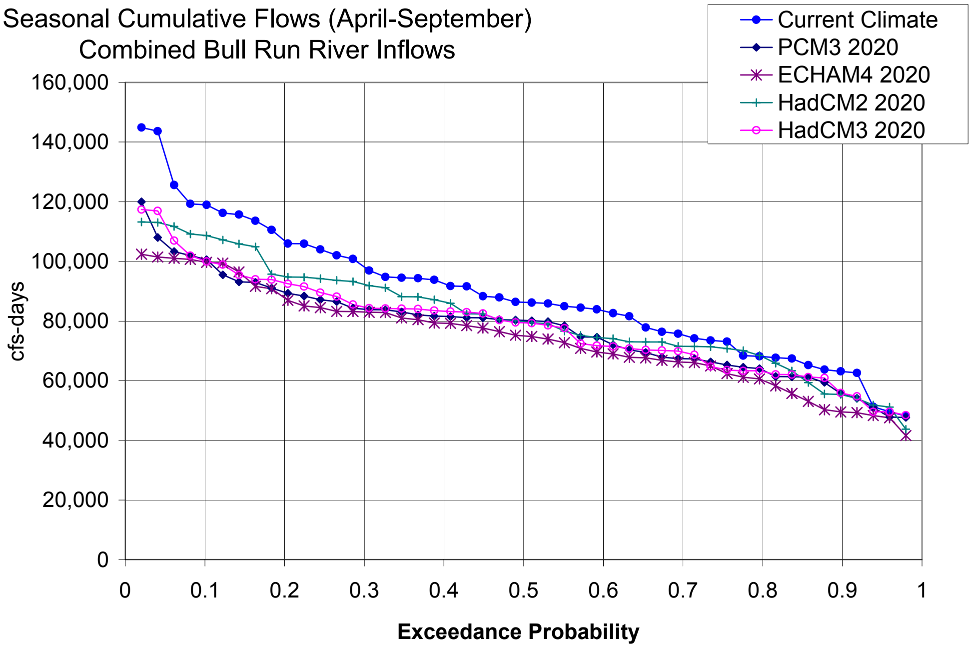


Figure 41 - Exceedance Probability for Seasonal Cumulative Flows (April-September) for the 2020 Climate Change Scenarios

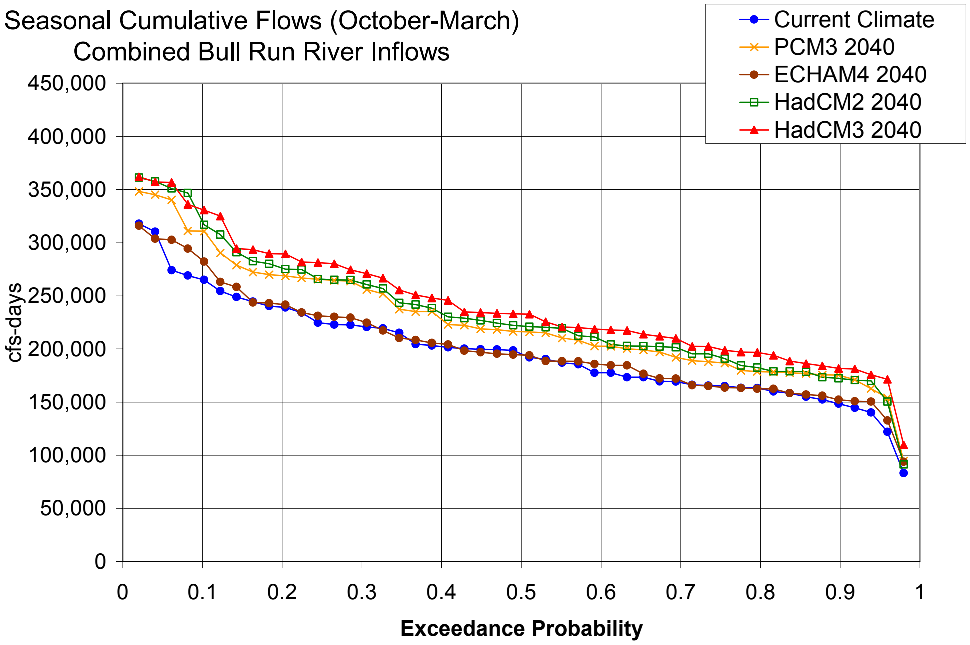


Figure 42 - Exceedance Probability for Seasonal Cumulative Flows (October-March) for the 2040 Climate Change Scenarios

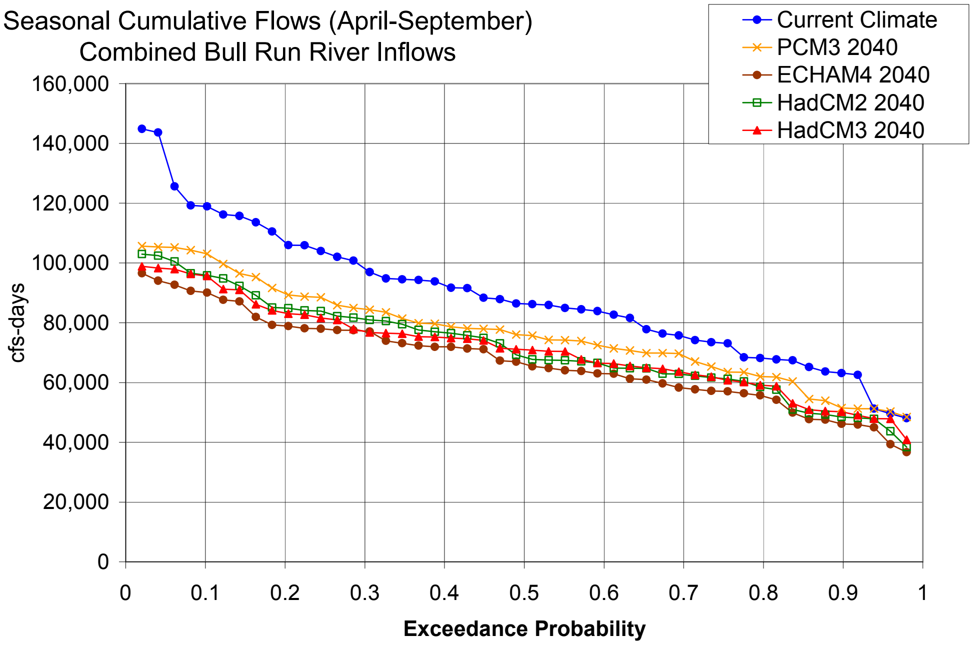


Figure 43 - Exceedance Probability for Seasonal Cumulative Flows (April-September) for the 2040 Climate Change Scenarios

A plot of cumulative annual summer flows (Figure 44) reveals years respond differently to climate change. Climate change can have a relatively small impact on annual cumulative summer flows, or a very large impact. The years chosen in this analysis for particular scrutiny include: 1952, 1966, 1968, 1982, 1987, 1992 and 1994. Four of the years commonly are used to describe hydrologic events with particular return periods: the 1 in 30 year event (1987), the 1 in 20 year event (1992) and 1 in 10 year event (1994) and the average year (1982). Other years, 1952 and 1966, were chosen because they are significantly impacted by climate change. One other year, 1968, was chosen to represent a relatively wet year.

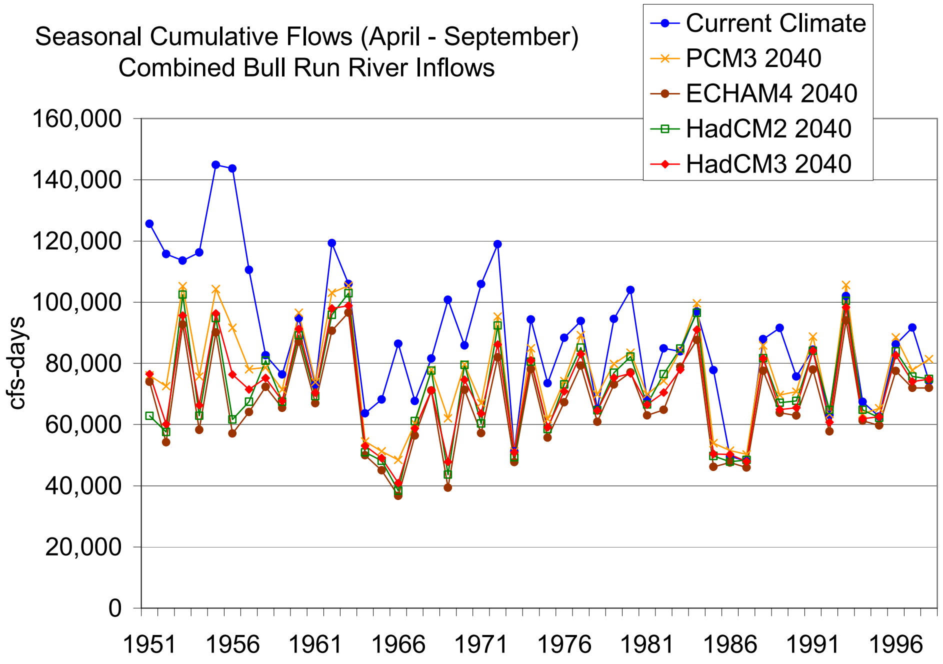


Figure 44 - Seasonal Cumulative Flows (April – September), Combined Bull Run Inflows

Impacts of climate change on the analysis years are shown in Figure 45 through Figure 58 for both 2020 and 2040 climate change. The changes in flow due to climate change are the greatest in 1952 and 1966, as these years show higher winter flows and lower spring flows indicative of the climate change signals. The average year responds similarly but to a lesser degree. The system traditionally defined drought years are impacted very little by the climate change signal.

The hydrograph of the 1966 flows shows the typical shift in a climate change scenario. The other low flow climate change years have a similar shape with higher flows in the winter, a dramatic decrease in the spring melt, and an earlier onset of the spring recession curve.

In this study, 1982 has been defined as an “average" or typical year. The time series hydrographs of 1982 (Figure 51 and Figure 52) shows a much less dramatic change in the spring flow recession when compared to the 1966 flows in Figure 53 and Figure 54.

When the climate change signal is applied to the drought years, 1987 and 1992, there is little impact. The 1987 drought can be characterized as a late fall drought. Spring and early summer flows were not low, but the typical fall rains did not return until late December. In fact, the winter temperatures in 1987 were lower than average, and the climate change signal did not prematurely melt the snowpack. Because there were no fall rains, changing their percentage in the climate change evaluations had little impact in the hydrology.

The 1992 drought was almost the mirror image of the 1987 drought with much lower than normal snowpack to start the year. Precipitation was sufficiently low and temperatures significantly high in the spring that the climate signal calling for a percentage more precipitation and higher temperatures in the winter did not contribute significantly to the base hydrology.

These analyses indicate that two important drought years (1987 and 1992) that have helped define the system's safe yield historically are not impacted by climate change. This does not imply that other years will not be impacted significantly. Years like 1952, 1966, and 1982 are impacted by climate change and, in fact, may prove to be important in evaluating the performance of the system in the future.

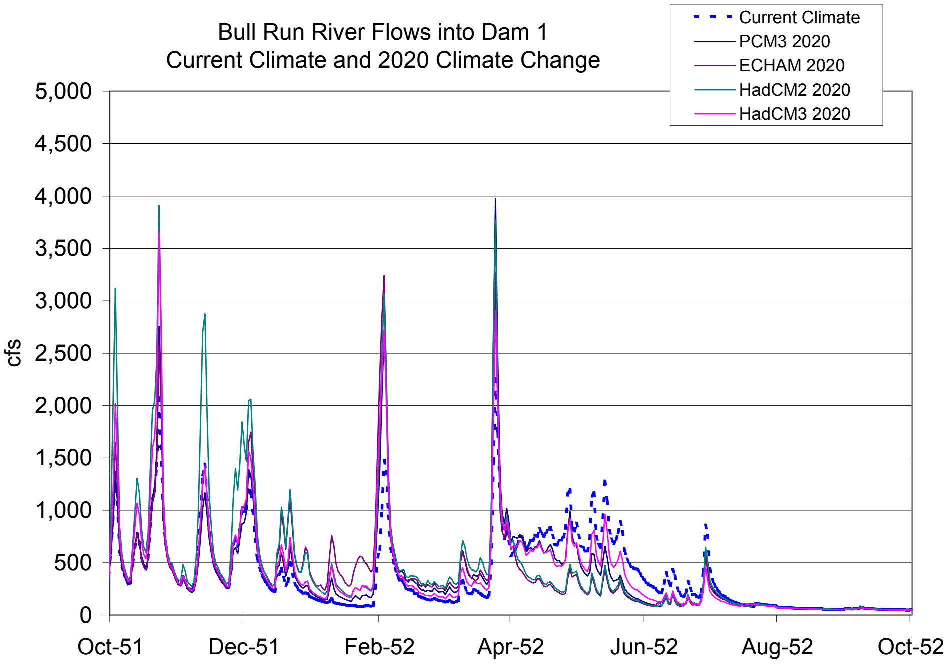


Figure 45 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1952

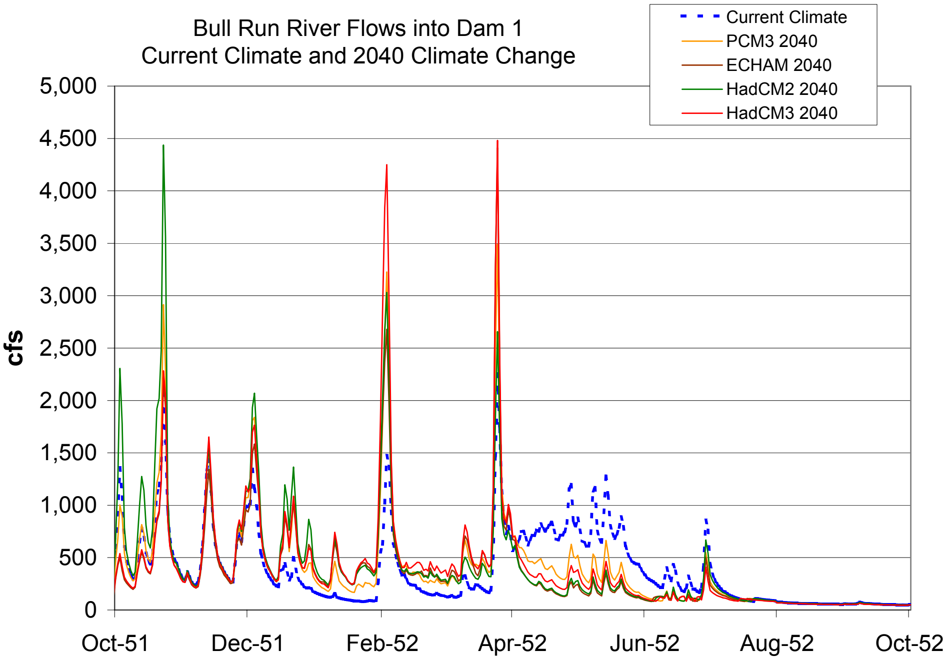


Figure 46 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1952

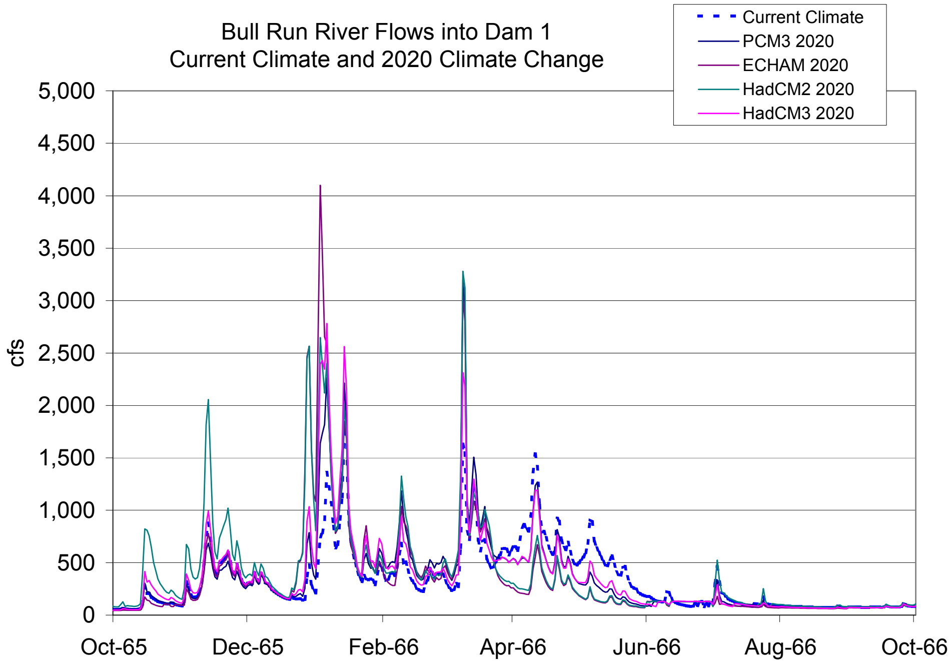


Figure 47 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1966

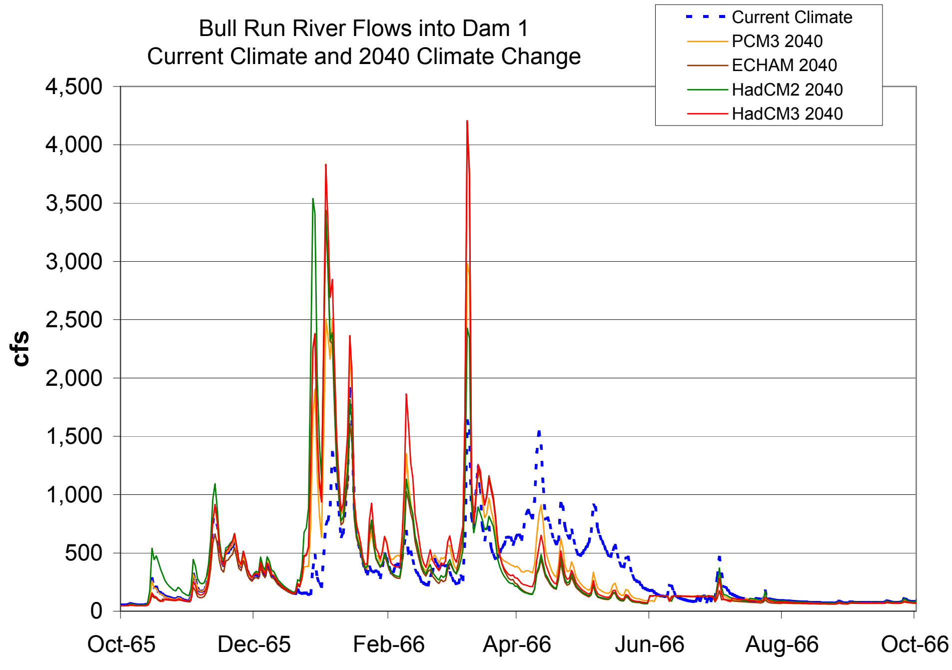


Figure 48 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1966

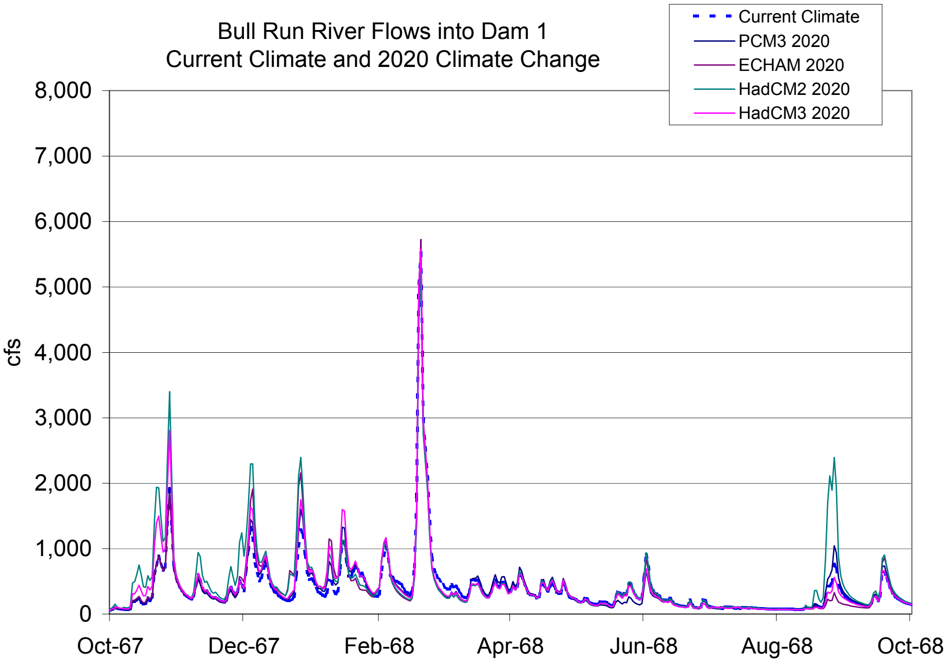


Figure 49 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1968

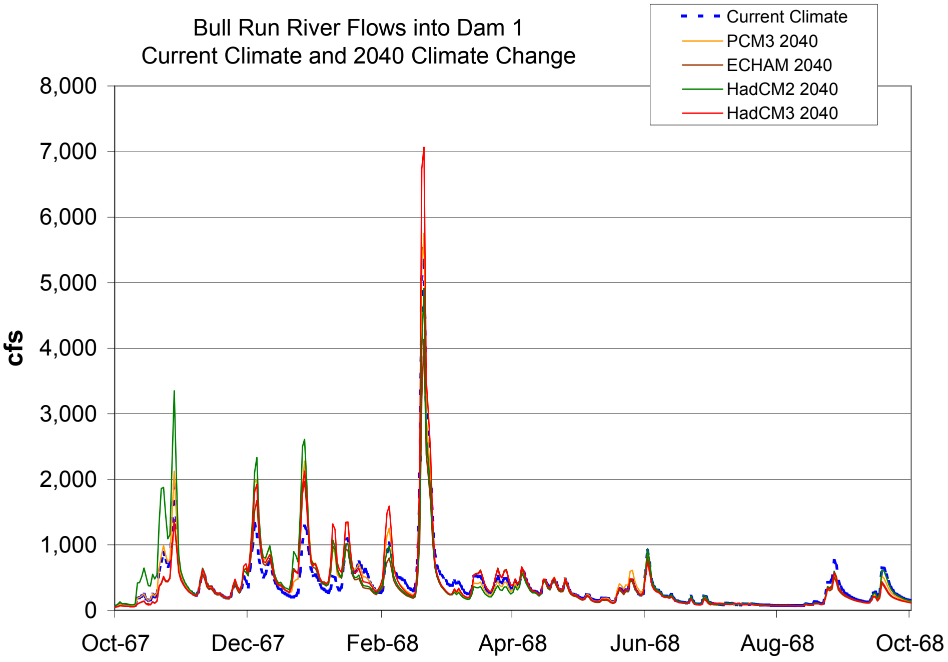


Figure 50 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1968

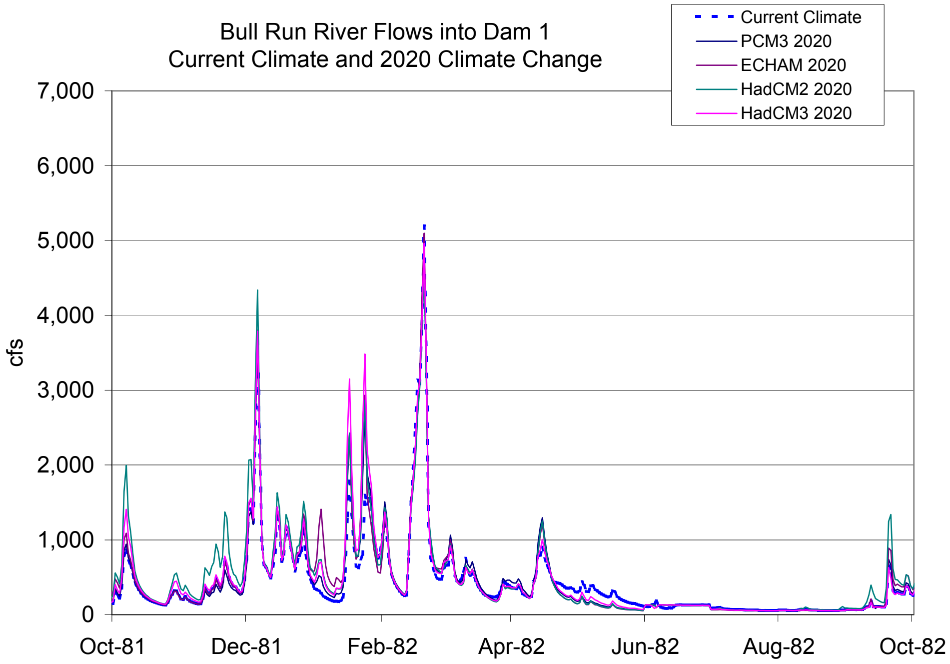


Figure 51 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1982

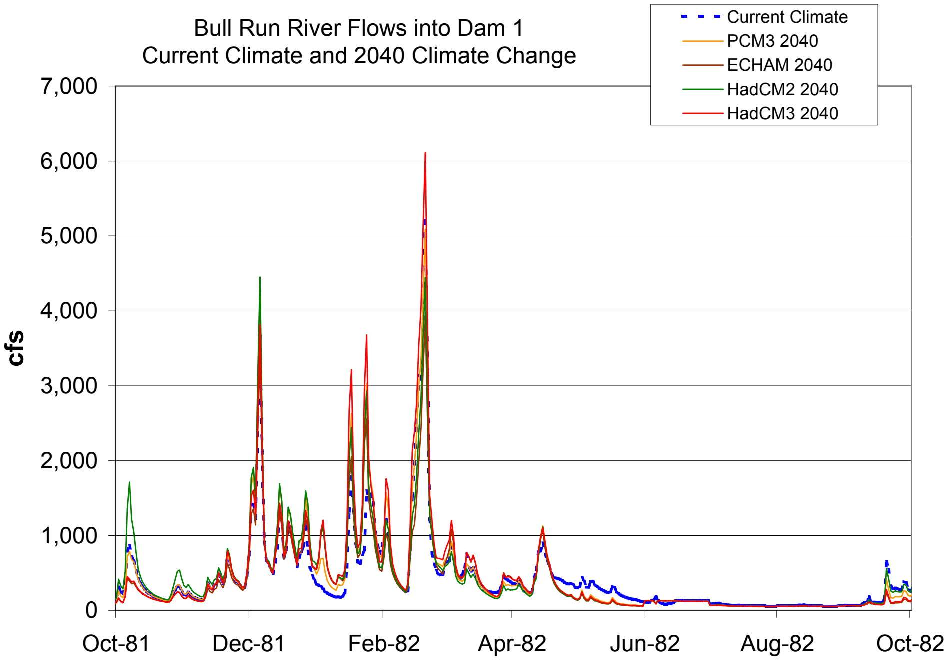


Figure 52 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1982

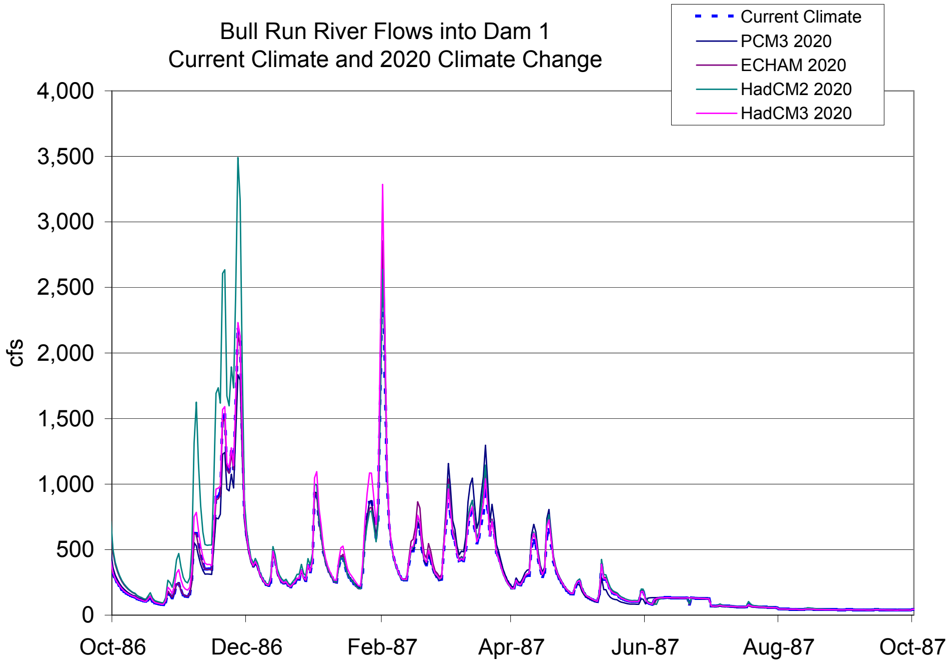


Figure 53 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1987

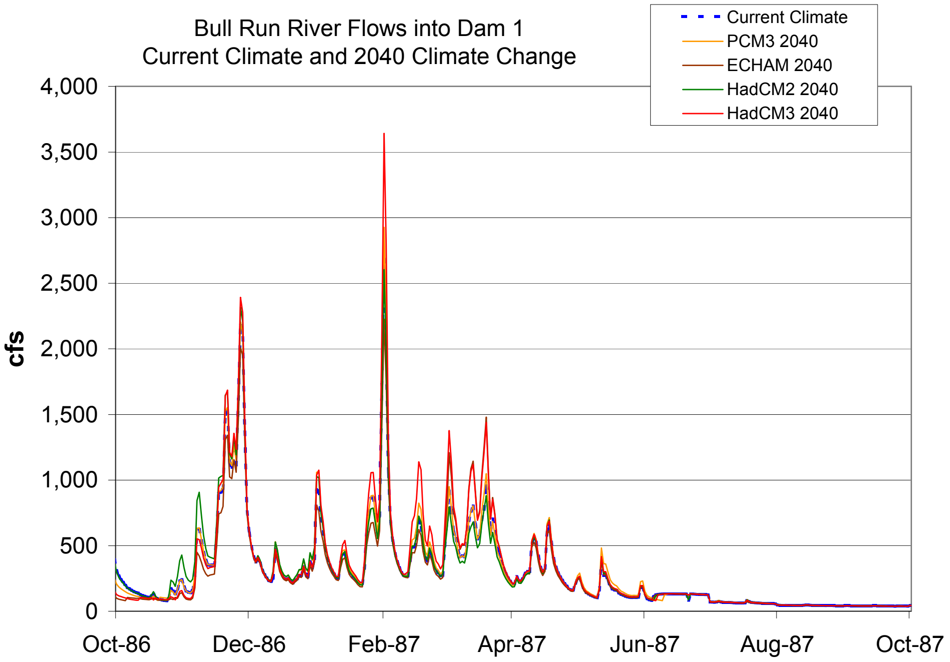


Figure 54 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1987

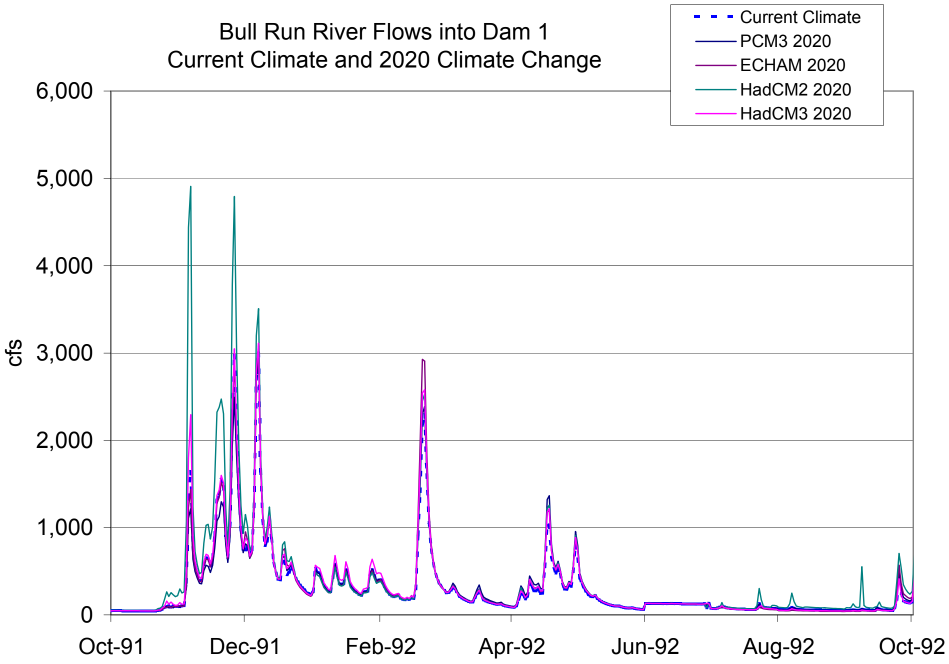


Figure 55 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1992

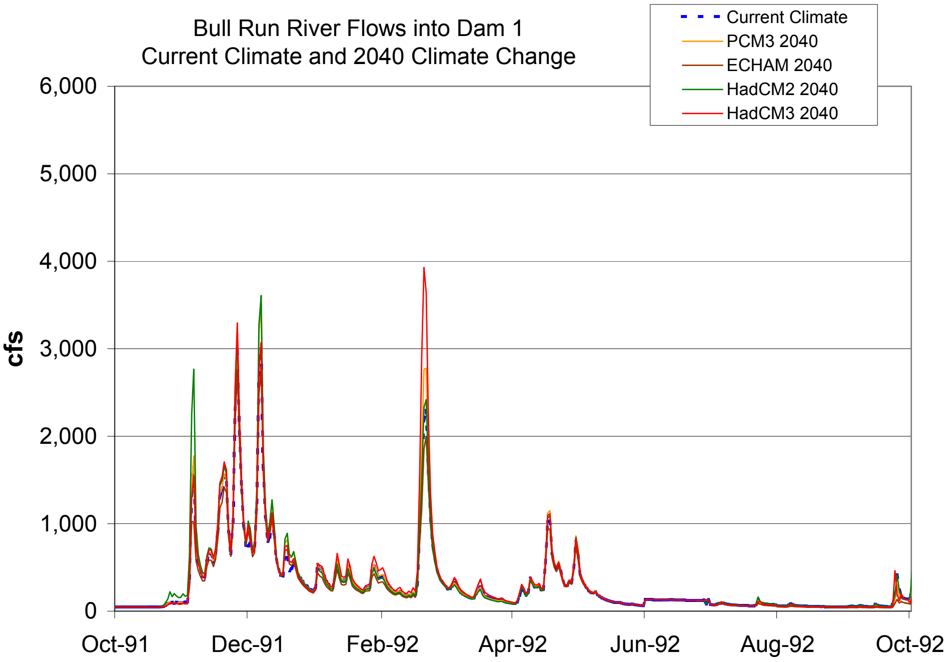


Figure 56 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1992

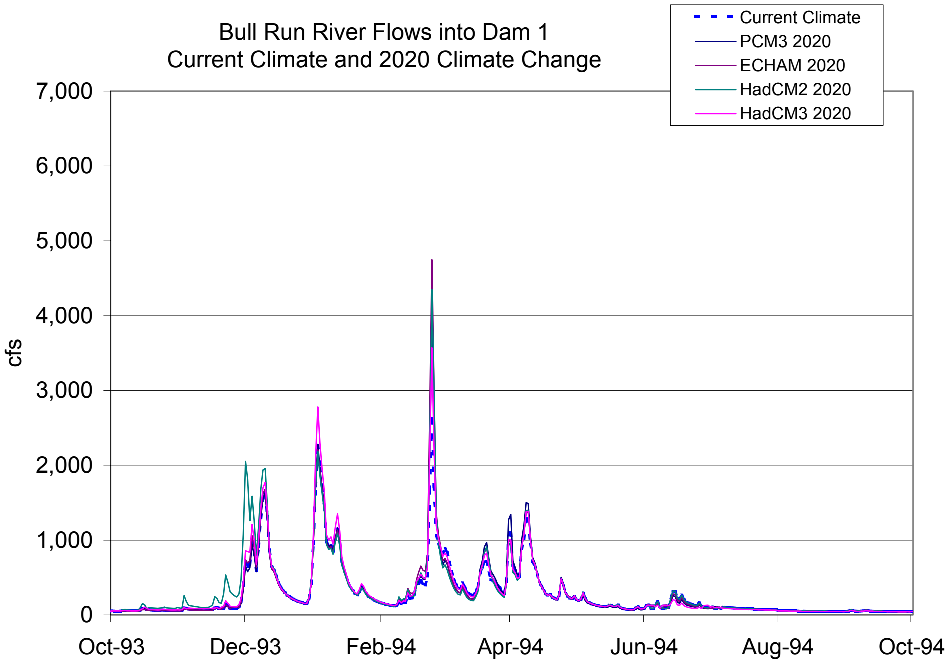


Figure 57 - Bull Run River Flows into Dam 1, Current Climate and 2020 Climate Change for 1994

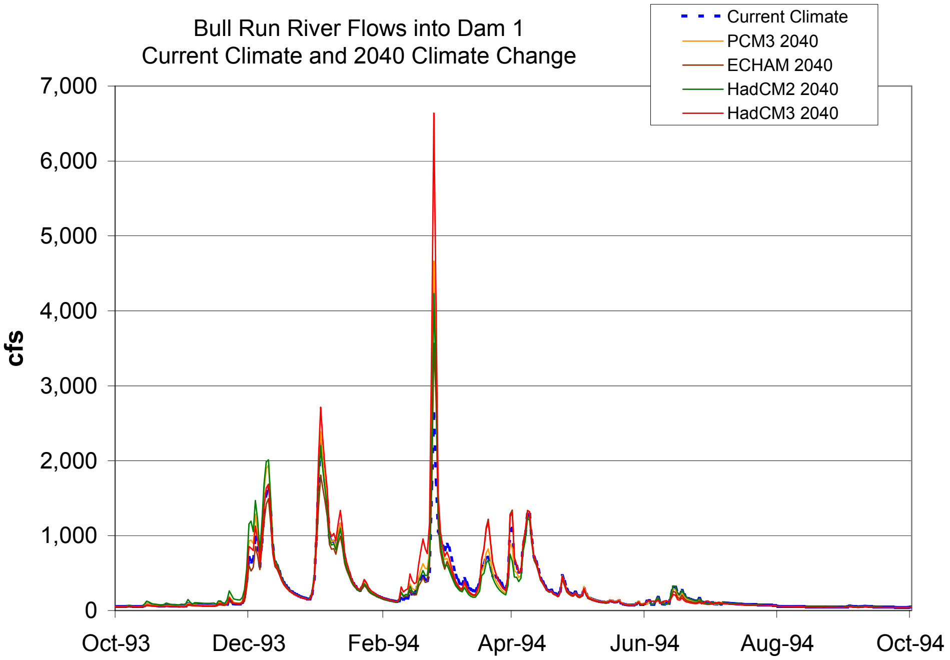


Figure 58 - Bull Run River Flows into Dam 1, Current Climate and 2040 Climate Change for 1994

Section 5 summarizes the impacts of climate change on streamflows. The impacts have been evaluated from several perspectives to clearly illustrate not only the total annual change in streamflow volumes, but to illustrate their timing and their seasonal importance. In most cases, winter flows will be greater and early summer flows less under climate change conditions. These results occur due to the synergetic effects of higher winter precipitation, changes in summer precipitation, and generally warmer temperatures.

In addition, it has been noted that not all years are impacted equally. For instance, one would not expect a major change in streamflows during the summer months for a year that had an initial low snowpack. The snow in a low snowpack year typically melts long before the summer months, with or without climate change. The years in which summer flows are most likely to be impacted are those that have a moderate to large amount of snowpack and for which the historic temperatures were mild, preserving the snow until the late spring and early summer. In these cases, a warmer climate signal may result in the snowpack melting prior to the mid-summer. The years in which the average winter temperatures are close to freezing are pushed from a transient basin hydrology to one that is more rain driven as shown in the years 1966, 1969, 1952, 1954 and 1971.

The impacts of climate change on water supply performance is discussed in the next section including exceedance probability curves of annual minimum storage for existing and future system infrastructure and the reductions in annual minimum storage volumes for the seven featured years.

6. Model Results - Supply and Transmission Model

After calculating the impacts of climate change on streamflows, these climate-altered streamflows are used to evaluate their influence on water supply performance with the STM. Several configurations of current and future conditions are reviewed. Because the study's primary purpose is to evaluate the potential impacts of climate change, it is essential that these impacts not be concealed by the impacts of future water demands. Special care has been taken to separate these impacts and represent each distinctly.

The STM is used to examine the supply and demand system under climate conditions and to compare the impacts of climate change with other key components. The results are presented in three evaluations. The first evaluation compares the climate impacts on hydrology and the impacts of regional water demands on system performance. This evaluation uses the current infrastructure and a 49-year record to generate exceedance probability curves with which to quantify impacts of climate change on hydrology and the impact of regional growth on demand.

The second evaluation also uses the current system, but investigates the seven featured years in greater detail. The evaluation presents the different impacts (climate impact on hydrology, climate impact on demand, growth impact on demand) separately and then jointly. The ECHAM4 climate scenario is chosen for the detailed analysis in the second and third evaluations because it has a relatively consistent signal between the 2020 and 2040 decade and has the greatest impact on hydrology.

The third evaluation exercises two planning strategies for the seven featured years. The planning strategies are denoted as "System Expansion and Reliance on Groundwater" and "Build Dam 3." The planning strategies are compared and assessed by the impacts of regional growth and the climate impacts on hydrology and demand. The results are based on the yearly drawdown cycle for the featured seven hydrologic years. Insights are drawn based on the careful consideration of these seven years. The two planning scenarios are further exercised with the 49-year record. Exceedance probability curves of the annual minimum storages and the amount of groundwater pumped contrast the two planning strategies and develop the framework for discussing the sustainability of Portland's water supply system.

The three system configurations used in the analysis (Table 2): SC1 – Status Quo without Groundwater, SC2 – System Expansion with Reliance on Groundwater, SC3 – Build Dam 3 are derived from the PWB Infrastructure Master Plan. The system configurations consider only the existing service area and assume no conservation efforts. The system configurations are described below and are detailed in Appendix C: System Configurations for Climate Change Study STM Model Runs.

Table 2- System Configuration Descriptions.

SC1 - Status Quo Without Groundwater The Status Quo models the current system configuration (year 2000) without the use of groundwater. This scenario is the control case.
SC2 - Baseline with Conservation Same as SC1 with the addition of the groundwater (Columbia South Shore Wellfield). The groundwater operating procedures for this system configuration include a supply rate based on days of supply remaining, a pumping rate of 70 million gallons per day (mgd) for 2000 and 90 mgd for 2020 and 2040, and a maximum native ground water volume of 6.6 billion gallons. This configuration expands the supply in the Bull Run system by raising the top of storage of Dam 1 and Dam 2.
SC3 - Dam 3 Adds Dam 3 to system expansion, but does not include raising Dam 1 or treating Dam 2 dead storage. This scenario continues to serve the existing service area.

The STM illustrates several important results in differentiating the impacts of climate change alone and the impacts of growth. When the impacts are considered jointly, they can consume as much as 12 billion gallons in storage by 2040. In comparing the two planning scenarios, the results show the contrast between developing more surface water and increasing reliance on groundwater.

These results are presented in terms of the annual minimum storage less shortfall, the length of the drawdown period and the amount of groundwater pumped during the drawdown period. The annual minimum storage for a specific demand climate scenario is compared to the annual minimum storage for the current climate with 2000 demands.

It is important to note the interplay between streamflows, system yield, and the availability of storage in the reservoir as expressed in its rule curve. The rule curves used in this system can have a significant impact on yield. For systems that have a large storage volume relative to streamflows, the timing of runoff will have little impact on system reliability; instead, the volume of runoff is the essential feature. For systems like the Portland supply for which the annual runoff is larger relative to the storage volume, the timing can be very important. Water may be available in the early spring when it is spilled, but not available in the summer when it is needed.

6.1. Evaluation 1 : Ranked Annual Minimum Storage less Shortfall for SC1

A primary measure of a system's performance is the minimum storage during the year. If storage decreases below established thresholds, water reliability is compromised, the system is not seen as sustainable, and curtailments may be required. In the first evaluation, ranked annual minimum storages are presented. Figure 59 to Figure 62 present the ranked minimum storage less shortfall[*] for combinations of demand year and climate change year. Specifically, Figure 59 presents the storages associated with the demand year 2000 and the climate change year 2020. Figure 60 illustrates demand year 2000 and climate year 2040. Figure 61 illustrates demand year 2020 and climate year 2020. Figure 62 presents demand year 2040 and climate year 2040. These ranked storages estimate the probability of storages being at or below a specific value. The individual curves estimate the probability associated with specific climate/demand combination. Key information from these curves includes 1) the change in minimum storage less shortfall between curves for a given probability and 2) the change in probability between curves for a given storage.

The curves show that for a given probability, the storage values for the current climate / 2000 demand curve are greater than those of the changed climate. The exception to this is HadCM2 2020 (Figure 59 and Figure 60). This scenario has higher streamflows as well (Figure 40). The other three 2020 climate scenarios are similar. Differences in the storage values for the 2040s are consistent and range between 0 and 1 billion gallon difference in minimum storage less shortfall for both the 50% and 90% probability. The minimum storages for the 50% and 90% probabilities are shown in Table 3.

Figure 61 and Figure 62 are the exceedance probability curves for minimum storages for the climate change scenarios and regional growth associated with 2020 and 2040. Here the impact of demand has a 4 billion gallon reduction in storage at the 50% exceedance level.

The curves also show the change in probability for a given storage. For example, the storage associated with the 90% exceedance probability for a current climate with 2000 demands (9,082 mgal) is reduced to an exceedance probability of 75% for the ECHAM4 2040 climate and 2000 demands. This indicates that a storage value associated with a 1 in 10 event today may be associated with a 1 in 4 event by 2040. A similar trend is seen in the case of the storage values associated with the 50% exceedance probability for both the 2020 and 2040 scenarios.

Exceedance probability curves are also developed for the difference in minimum storages less shortfalls for the system for 2040 demand and 2040 climate change from current climate and 2000 demand. In approximately 40% of the years, climate change impacts by the year 2040 would decrease minimum system storage by more than 1 billion gallons each year. At the 50% probability level there is a 5.5 billion reduction in storage for 2040 regional growth and 6.5 for climate change and demand in 2040.

The annual minimum storages are presented in Figures 1-B through 4-B of Appendix B: Figures and Tables. The data identify specific years that are more sensitive to climate change, such as 1952 and 1966, and those years that are not as sensitive, such as the drought years 1987 and 1992.

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[*] The volume of unmet demand is the "shortfall". If the system could not meet all demands in a particular year, the shortfall is subtracted from the minimum storage.

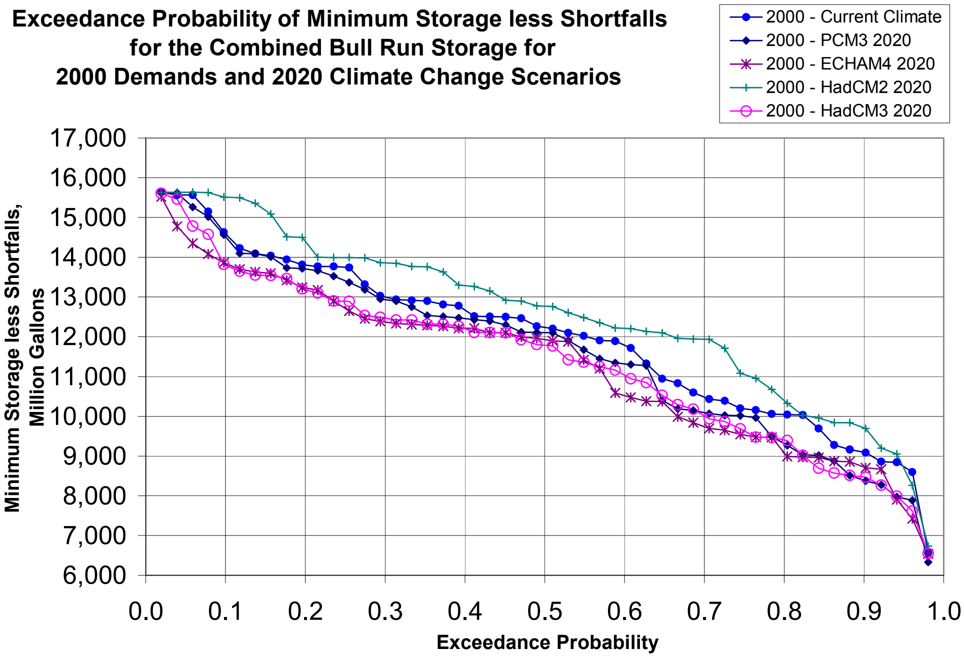

Figure 59 - Exceedance Probability Curve for Minimum Storage less Shortfalls for the Combined Bull Run Storage for 2000 Demands and 2020 Climate Change Scenarios

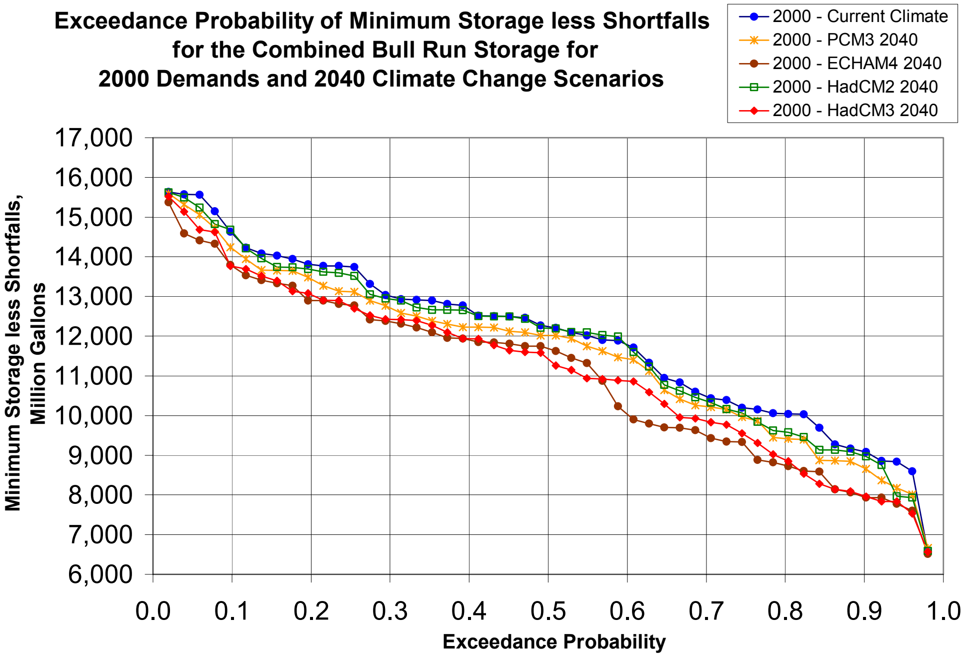

Figure 60 - Exceedance Probability Curve for Minimum Storage less Shortfalls for the Combined Bull Run Storage for 2000 Demands and 2040 Climate Change Scenarios

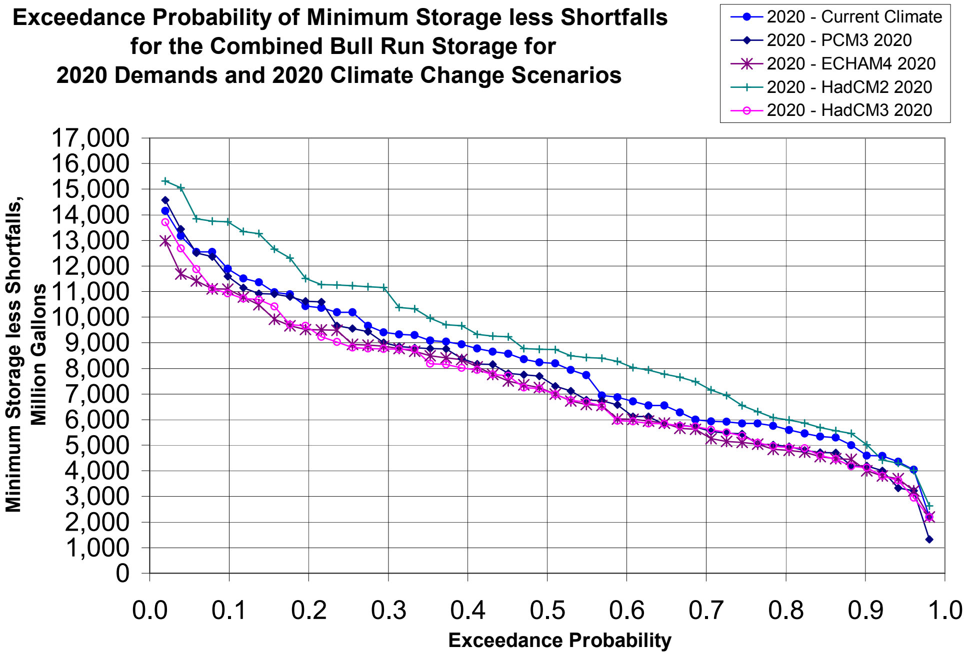

Figure 61 - Exceedance Probability Curve for Minimum Storage less Shortfalls for the Combined Bull Run Storage for 2020 Demands and 2020 Climate Change Scenarios

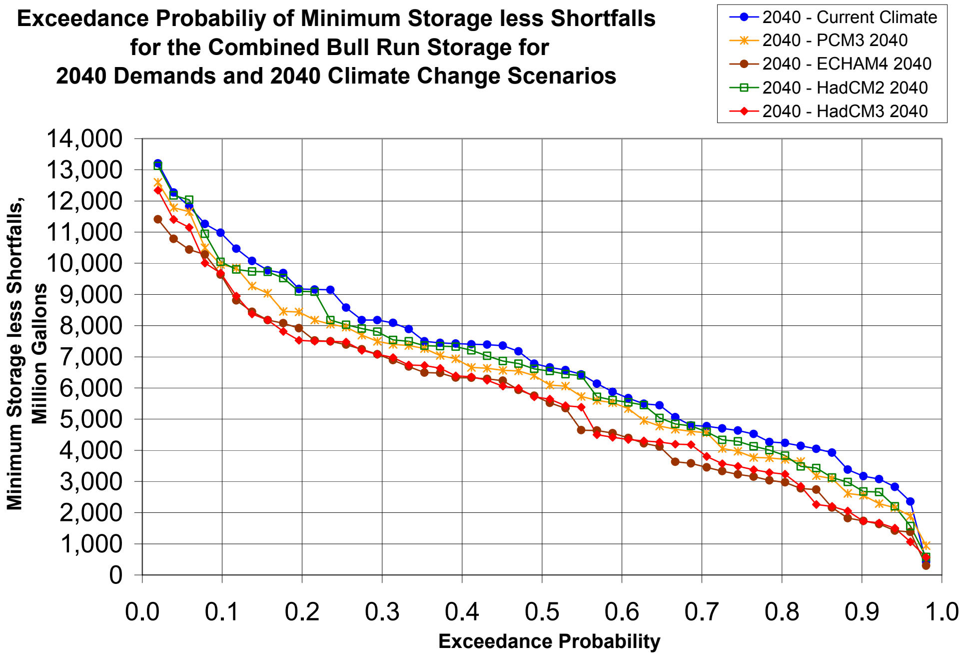

Figure 62 - Exceedance Probability Curve for Minimum Storage less Shortfalls for the Combined Bull Run Storage for 2040 Demands and 2040 Climate Change Scenarios

Table 3 - Minimum Storage less Shortfall (million gallons) for 50% and 90% Exceedance Probabilities Varying by Climate and Demand Scenarios

Demand year	2000		2000		2020		2040	
Climate Scenarios	2020		2040		2020		2040	
Exceedance Probability	50%	90%	50%	90%	50%	90%	50%	90%
Range for Climate Change Scenarios	12,762 to 11,768	9,697 to 8,376	12,211 to 11,257	8,966 to 7,959	8,740 to 6,988	5,017 to 4,122	6,615 to 5,525	2,677 to 1,729
Current Climate	12,208	9,082	12,208	9,082	8,195	4,603	6,657	3,169

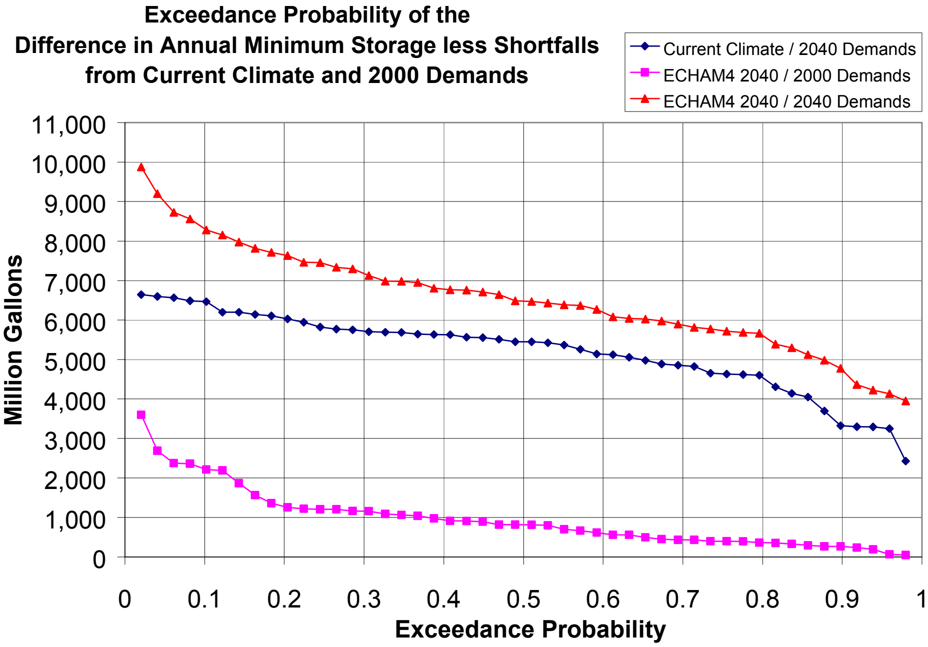

Figure 63 – Exceedance Probability of the Difference in Minimum Storage less Shortfalls from the Current Climate and 2000 Demands for the Combined Bull Run Storage

6.2. Evaluation 2: SC1 Analysis for Seven Featured Years

The second evaluation includes the impact of climate change on demand, which is calculated with data provided by Dr. Hossein Parandvash of PWB. The process for calculating the climate impact on demand is provided in the Joint Institute on the Study of Atmosphere and Oceans (JISAO) report on "Impacts of Climate Variability and Change in the Pacific Northwest" (JISAO 1999). The impact on demand is calculated based on a change in average temperature and precipitation and then applied to the weather data that are input to an econometric model. The peak season demand is increased approximately 8% and the average annual increase in demand is 4%. As previously described in Section 2, seven of the 49 years have been chosen as feature years to perform a more detailed assessment of climate impacts. The impacts of climate change on demand are not available for all 49 years, however, the seven years chosen provide insight into the response of the system for average years and for the hydrologic and weather extremes.

Numerous STM runs were made with different combinations of demand and climate to evaluate the impacts. The impact is calculated as the difference in minimum storage less shortfalls between climate/demand combinations for each year. Figure 64 presents the impacts on the seven years using the ECHAM4 climate change scenario. The impact of climate change on hydrology and demand vary between years. The sensitivity of hydrology to weather is greater than that of demand. The climate change impact on both demand and hydrology is calculated to be between 5,366 mgal (1966) and 1,188 mgal (1968).

The results of Figure 64 can be summarized as the following: for the case of the seven hydrologic years, average minimum storage will decrease by about 4.1 billion gallons by 2020 and 5.5 billion gallons by 2040 due to growth in demand alone. This stress on the system is exacerbated by the impacts of climate on hydrology and demand in the future, decreasing the average storage by 8 billion in 2020 and 9.6 billion in 2040.

Table 4 presents the average of the seven years, the number of days of drawdown and the loss in yield. Remaining yield is the annual minimum storage value divided by the number of days of drawdown, and it represents the volumetric rate of water that could have been used or that is still remaining. Loss in yield is the difference between the remaining yield of the alternative (2040 climate change impacts on hydrology and demand and regional growth impact on demand) and the base case (current climate / 2000 demands).

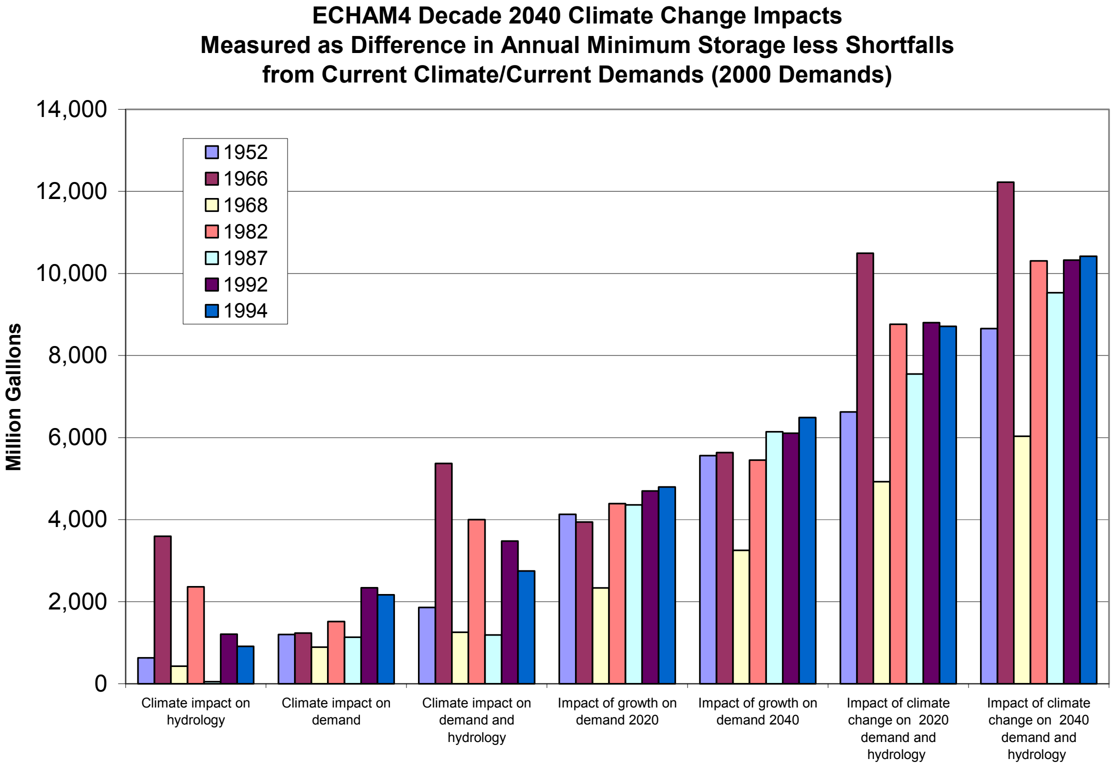

Figure 64 – Impacts of Climate Change (ECHAM4 2040) and Regional Growth (2040) as Measured as the Difference in Annual Minimum Storage less Shortfalls from Current Climate / 2000 Demands

Table 4 - Impacts of Climate Change (ECHAM4 2040) and Regional Growth (2040) Measured as the Difference in Annual Minimum Storage less Shortfalls from Current Climate / 2000 Demands (values from Figure 64, million gallons).

Year	Climate impact on hydrology	Climate impact on demand	Climate impact on demand and hydrology	Impact of growth on demand 2020	Impact of growth on demand 2040	Impact of climate change on 2020 demand and hydrology	Impact of climate change on 2040 demand and hydrology	Number of days of drawdown	Loss in Yield - Impact of climate change on 2040 demand and hydrology
1952	629	1,200	1,859	4,127	5,562	6,627	8,657	149	12
1966	3,598	1,232	5,366	3,943	5,633	10,491	12,225	167	32
1968	431	892	1,255	2,334	3,251	4,921	6,034	54	23
1982	2,363	1,512	4,003	4,393	5,449	8,762	10,303	134	30
1987	49	1,135	1,188	4,361	6,141	7,547	9,532	176	7
1992	1,208	2,339	3,476	4,697	6,106	8,800	10,327	141	25
1994	911	2,166	2,748	4,794	6,485	8,713	10,419	172	16
Average	**1,313**	**1,497**	**2,842**	**4,093**	**5,518**	**7,980**	**9,643**	**142**	**21**

The average loss of yield for the seven years is 21 mgd during drawdown. For years like 1968, the yield of the system is large and losing 23 mgd does not compromise system reliability. For drought years, this is a significant problem. For those years whose ranking changes due to significant climate impacts on hydrology, the loss of yield is an emerging and potentially significant problem. Figure 65 compares the loss in yield to the actual remaining yield.

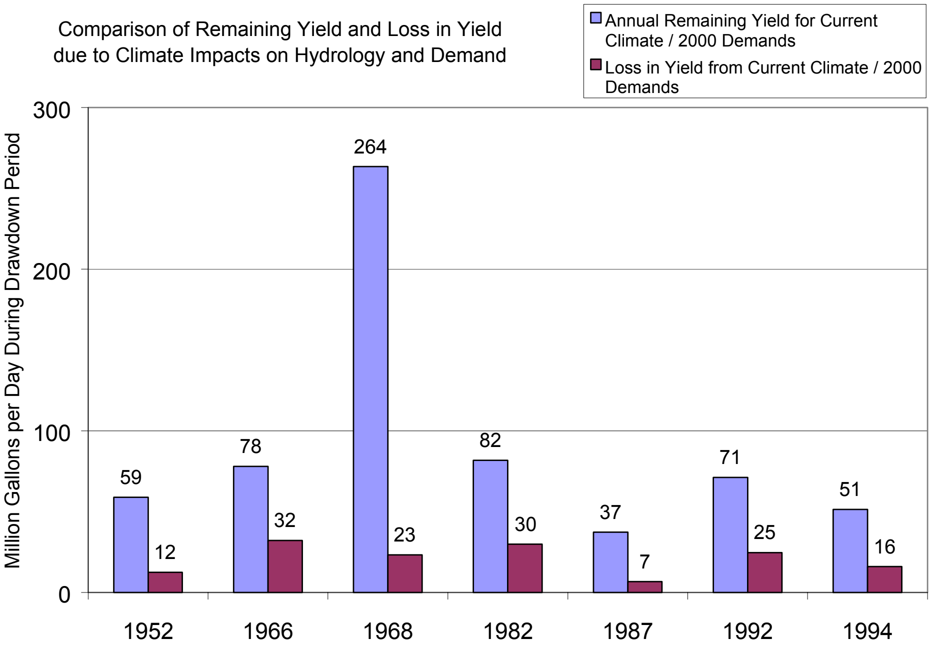

Figure 65 - Comparison of Remaining Yield and Loss in Yield due to Climate Impacts on Hydrology and Demand

The evaluation of the seven featured years highlights several conclusions about the impacts of climate change. First, the average impact of climate change on hydrology is a 1 billion gallon reduction in storage, but can be as great as 3.6 billion gallon (1966 hydrology). Second, the impact of climate change on demand results in an 8% demand increase during the peak season which results in an average 1.5 billion gallon reduction in storage and as much as 2.3 billion gallons (1992). The average combined impact of climate (on both demand and hydrology) is 2.8 billion gallon reduction in storage with the largest impact from 1966 hydrology of a 5.4 billion gallon storage reduction. The impacts on the system of climate change exacerbate the impacts of regional growth, creating an average of 9.6 billion gallons of reduction in storage and can be as great as a 12.2 billion gallon reduction for the 1966 hydrology.

The final evaluation compares two existing planning scenarios with the overall impacts of climate change (demand and hydrology) and the growth impact on demand. The evaluation uses the seven featured years and the concept of remaining yield. The two planning scenarios are compared for the 49 year period with exceedance probability curves.

6.3. Evaluation 3: Comparing Two Planning Scenarios, SC2 and SC3

Evaluation 3 uses two planning scenarios to demonstrate how existing and viable planning strategies will perform under the stresses of climate and growth impacts. The planning strategies or scenarios implement infrastructure changes to the system to maintain system reliability as demand increases with population. The scenarios considered here are SC2 - System Expansion and Reliance on Groundwater and SC3 - Build Dam 3. The seven featured years (1952, 1966, 1968, 1982, 1987, 1992, and 1994) are assessed with five demand/climate combinations for the two planning scenarios:

1) current climate / 2000 demands (*base case*),
2) current climate / 2020 demands (*impact of growth in 2020*),
3) current climate / 2040 demands (*impact of growth by 2040*),
4) ECHAM4 2020 hydrology / ECHAM 4 2020 demands (*climate impact on hydrology and demand by 2020*), and
5) ECHAM4 2040 hydrology / ECHAM4 2040 demands (*climate impact on hydrology and demand by 2040*).

The STM assessments for the 70 model runs evaluate annual performance and metrics specifically for the drawdown period. Some of these metrics include total annual storage used, average annual demand, average demand during the drawdown cycle, annual minimum storage and the volume of groundwater pumped during drawdown. The metrics for each run are tabulated in Appendix B: Figures and Tables. The metrics reported here are annual minimum storage, volume of groundwater pumped during drawdown and the number of days of drawdown (for the 2040 climate and demand scenarios). Two additional metrics are used in this evaluation, *remaining yield* (previously discussed) and the *drawdown groundwater pumped.* This metric is the daily rate of groundwater pumped during the drawdown period and is derived by dividing the total amount of groundwater pumped during the drawdown cycle by the number of days of drawdown.

Both of the planning scenarios are viable planning options taken from the PWB's Infrastructure Master Plan. As such, the scenarios meet instream flow requirements and municipal and industrial demands for all growth and climate scenarios assessed. The comparison of the planning scenarios reveals vulnerability and resilience of the system for specific planning scenario alternatives in terms of the amount of storage remaining and the amount of groundwater pumped.

Figure 66 compares the minimum storages of the two planning scenarios as well as the volume of groundwater pumped in SC2. The minimum storages for SC2 remain relatively constant between current and changed climate since the groundwater meets the additional demand and compensates for the climate impacted flows. SC3, which relies solely on surface water provided by Dam 3, experiences a decrease in storage ranging from 8.3 billion for 1966 and 2.3 billion gallons for the wet year, 1968. Another comparison between the two scenarios is that the minimum storage in SC2 for the wettest year analyzed (1968) is only 1.7 billion gallons greater than the minimum storage in SC3 for the driest year analyzed (1987).

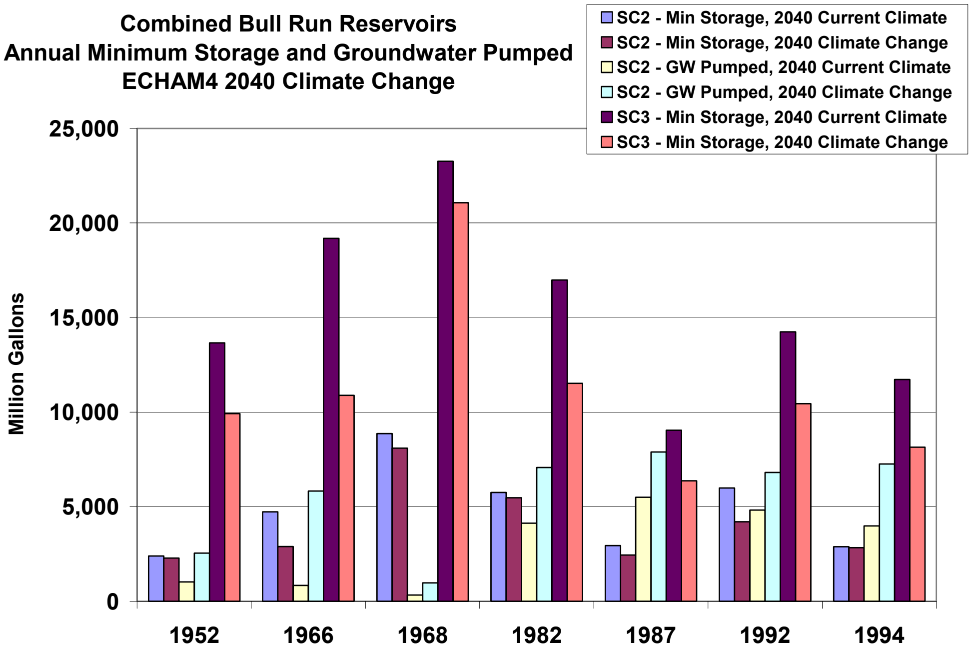

Figure 66 - Annual Minimum Storage, Combined Bull Run Reservoirs, Scenario 2 and 3 for Current and Changed Climate

The remaining yield and drawdown groundwater pumped values are presented in Figure 67 and summarized in Table 5. For both planning scenarios, there is more remaining yield and less groundwater pumped for the current climate runs than for the climate change runs. Also, there is more remaining yield for SC3 than there is for SC2 even though SC2 pumps groundwater heavily. For SC3, no groundwater is pumped and the remaining yield is 52 mgd on average. SC2 pumps an average of 38 mgd of groundwater during the drawdown period and has an average remaining yield of 20 mgd. For the current climate and 2000 demands, the average remaining yield for the six driest years of the seven is 41 mgd with an average drawdown groundwater pumped of 13 mgd (calculated with values from Appendix B). SC2, although meeting instream flow requirements and M&I demand, has half the remaining storage and pumps three times the groundwater of the current climate / 2000 demand system configuration.

SC3 results in large amounts of unused storage for most of the years. SC2 relies heavily on groundwater and represents the system completely expanded with the exception of Dam 3. SC2 is more vulnerable to the possible changes in system constraints, such as increased instream flow requirements, expansion of the service area or the implementation of a surface to groundwater ratio.

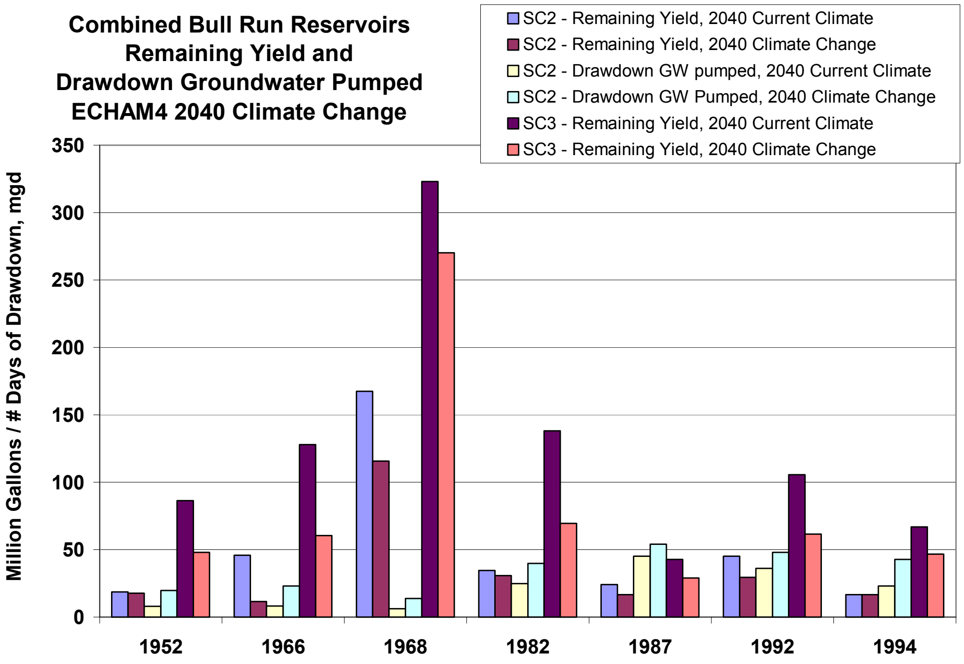

Figure 67 - Remaining Yield and Drawdown Groundwater Pumped, Combined Bull Run Reservoirs, Scenario 2 and 3 for Current and ECHAM4 2040 Climates

Table 5 - Remaining Yield and Drawdown Groundwater Pumped for SC2 and SC3.

	1952	1966	1968	1982	1987	1992	1994	Average excluding 1968
SC2 - Remaining Yield, 2040 Current Climate	19	46	167	35	24	45	17	31
SC2 - Remaining Yield, 2040 Climate Change	18	11	116	31	17	30	17	20
SC2 - Drawdown GW pumped, 2040 Current Climate	8	8	6	25	45	36	23	24
SC2 - Drawdown GW Pumped, 2040 Climate Change	20	23	14	40	54	48	43	38
SC3 - Remaining Yield, 2040 Current Climate	86	128	323	138	43	106	67	95
SC3 - Remaining Yield, 2040 Climate Change	48	60	270	69	29	61	47	52

The two planning scenarios are also assessed over the entire record for impacts of climate on hydrology and demand. The impact of climate change on demand is estimated as 8% during the peak season and 4% for the entire year. To apply a climate impact on demand for the 49 year period of record, the annual demand was increased by 10% with the assumption that the over estimation in the non-peak season would not greatly impact annual and drawdown metrics.

The annual minimum storage and volume of groundwater pumped during drawdown are calculated for each year in the period of record and presented in an exceedance probability plot, Figure 68. Several key features of the this plot are:

1) the range of minimum storages for SC2 is about half the range of minimum storages for SC3, 7.4 billion gallons vs. 16.4 gallons,
2) the range of groundwater pumped in SC2 is approximately equal to the difference of the range of minimum storages between the scenario, 14.1 billion gallons,
3) 50% of the time SC2 results in a minimum storage of 3.1 billion gallons and SC3 results in a minimum storage of 14 billion gallons,
4) 50% of the time, SC2 requires 5.3 billion gallons pumped during the drawdown period (37 mgd for 142 day average drawdown period),
5) 20% of the time, SC2 and SC3 retain 17.3 and 8.9 billion gallons of storage, respectively, and
6) 20% of the time, SC2 requires 2.6 billion gallons pumped during the drawdown (18 mgd for 142 day average drawdown period).

The sustainability of the two planning scenarios is based on management decisions about surface and groundwater use. Questions about what is sustainable with regard to groundwater use are important to address. Under SC2, for 50% of the years, groundwater pumped would average 37 mgd for 142 days. Also, for the SC2 case, the usable annual minimum storage is less than 3 billion gallons for 50% of the years. This is a much lower value of active storage than is experienced and leaves a small factor of safety for droughts more extreme than those experienced in the past. For current climate and 2000 demands, the remaining usable storage is 5.4 billion gallons for 50% of the years of record (Figure 63) and is 14 billion gallons for 50% of the time for SC3.

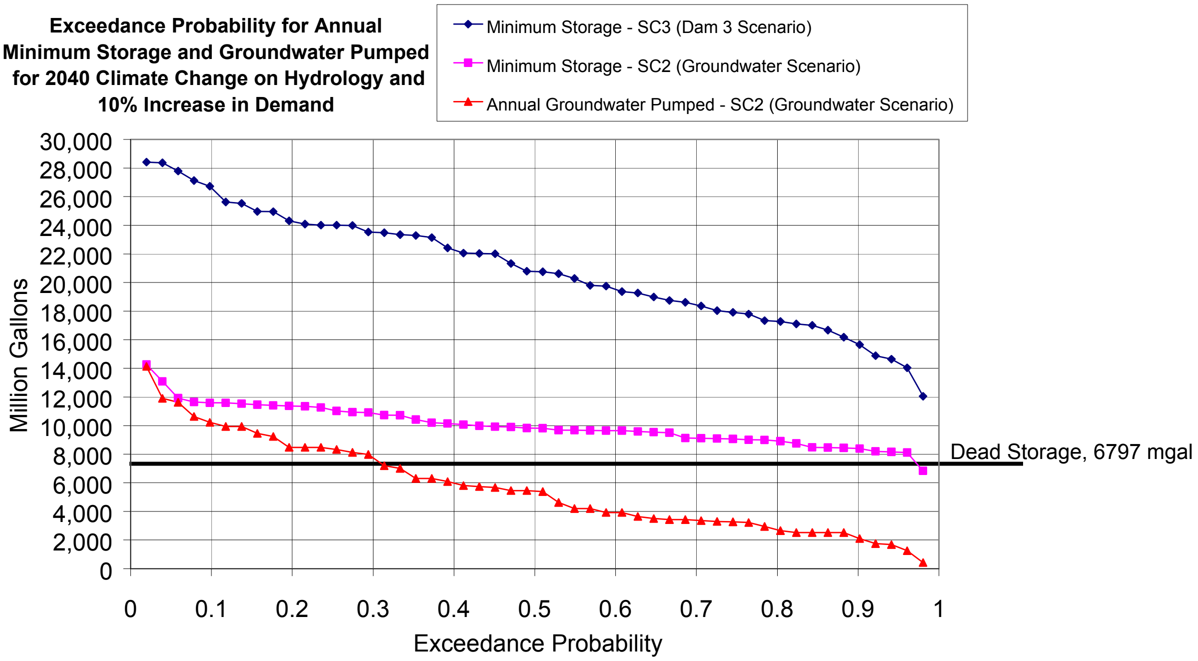

Figure 68 - Exceedance Probability for Annual Minimum Storage and Groundwater for 2040 Climate Change on Hydrology and 10% Increase in Demand.

These evaluations of the existing system and planning scenarios have demonstrated the response of the system's supply and demand to climate change and how this response can be shaped according to infrastructure decisions. The first evaluation demonstrates the magnitude of the different impacts on the system, showing on average a 2.8 billion gallon impact due to 2040 climate change and a 5.5 billion gallon impact due projected growth in 2040. Climate change therefore increases the constraints on the system in 2040 by 50% than attributed to growth alone. The joint impacts of the climate and growth on two viable Infrastructure Master Plan scenarios were tested and found reliable, although the sustainability of the scenarios depends upon the levels of remaining storage or the amount of groundwater pumped and the possible future constraints on the system. In one planning scenario, the system reliability for 50 % of the years relies on pumping 37 million gallons of groundwater daily during the drawdown period.

7. Conclusions

This study evaluates the potential impact of climate change on the Bull Run watershed and the performance of the Portland Water Bureau's water supply system. The study examines these impacts using a series of linked models that evaluate the climate change signal from four GCMs, the impacts of these climate signals on streamflows, and the impacts of these climate-altered streamflows on water supply performance.

The primary conclusion of this study is that climate change will have a significant impact on the hydrology of the Bull Run watershed and will impact the safe yield of the Portland water system. For seven typical dry years, climate change will reduce the amount of water that can be used to meet water demands by an average of 1.5 billion gallons and increase demand during the drawdown period by 2.8 billion gallons, resulting in 4.3 billion gallons of reduced minimum storage. This change will reduce the current safe yield of the years investigated by 21 mgd. These climate impacts exacerbate the need that exists to provide some 9.6 billion gallons of increased demands due to regional growth by 2040. This primary conclusion is based upon the following:

- Past streamflows in the Bull Run watershed are controlled predominantly by rainfall rather than snowpack. Snowpack does provide additional flows in the early spring (April), but these are typically exhausted before the supply system begins it drawdown in late June.
- The average climate change signal from the four general circulation models result in increased temperatures (1.5 - 2.0 °C) and slightly increased precipitation.
- The trend in the decade 2020 and decade 2040 is for wetter and warmer winters and drier and warmer summers. The Bull Run watershed responds to the climate change signals as higher flows in the winter, lower spring-time flows and an earlier spring recession.
- The impacts of climate change are not uniform from year to year. The years for which climate change will have the greatest impacts are those with high winter precipitation, cool winter and spring temperatures, and/or warm summer temperatures.
- The shift in the timing and volume of spring runoff in the Bull Run basin associated with climate change, particularly by 2040, will decrease the average maximum winter snowpack. This will result in an increase in the frequency of low flow in early summer. This shift will result in a number of droughts as extreme as 1992.
- In approximately 50% of all years, climate change impacts by the year 2040 would decrease minimum system storage by more than 1 billion gallons each year. This

decrease results from earlier spring runoff that cannot be captured in the reservoirs and lower summer flows due to the earlier streamflow recessions.

- An analysis of the 7 featured years reveals an average loss in annual minimum storage of 2.8 billion gallons due to the impacts of climate change on hydrology and demand. Although, continued growth in the M&I demand will have a more crucial impact on minimum annual reservoir storage than climate change (5.5 billion gallon reduction), the addition of climate change to growth results in a significant impact of an average reduction of 9.6 billion gallons reduction by 2040.

- The average loss in the annual safe yield for the ECHAM4 2040 climate scenario and the seven featured years is 21 mgd.

- The Infrastructure Master Plan scenarios tested provided sufficient surface or groundwater supply to meet the year 2040 demands when considering the impacts of climate change.

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Appendix A – Calibration Memos

University of Washington
Department of Civil and Environmental Engineering

TO: Joe Dvorak
FROM: Margaret Hahn and Richard Palmer
RE: DVSVM Calibration
DATE: June 28, 2001

This memo addresses a number of issues that you have raised concerning the calibration of the Bull Run DHSVM, including its status and estimated completion date.

Calibration

The entire meteorological record has been run through the DHSVM. This provided data for a more thorough analysis. With this data the DHSVM results were compared to the observed data for selected time periods and seasonally (months).

Annual average hydrograph for the entire record

The annual average hydrograph for the headworks of the Bull Run system for the historical and observed streamflow record is presented below.

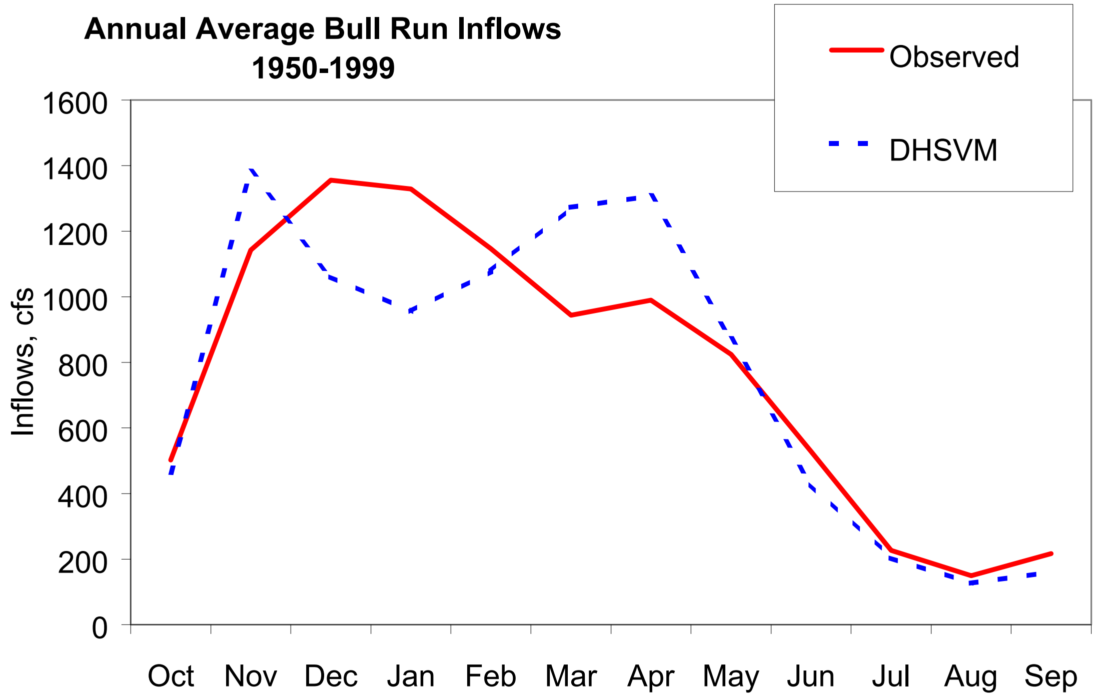


Figure 1. Average Annual Hydrograph for the Bull Run at Headworks, 1950-1999

The comparison of the two hydrographs reveals the following:

1) The annual flows are very similar. Over the fifty-year period, the total flows differ by 3%. This implies the model is capturing correct amount of flow in the basin.
2) The simulation closely estimates the peak flows by quantity.
3) The simulation closely estimates the return of the autumn flows in October and November as well as the recession curve and low summer flows May through September.
4) Snow accumulation is not being captured as well as is necessary nor is the snowmelt within the winter months. Although the model is representing the correct amount of precipitation within the basin, the ratio of precipitation falling as snow and rain is not correct. The model is recognizing too much of the precipitation as snow in the earlier part of the winter and releasing it as melt in the latter part of the winter.

There are two possible reasons for deviations from the model flows and actual flows. First, adjustments in the precipitation record in the basin made to better model annual flows (by scaling the available precip records) may have increased the modeled snow pack. Second, the model may not be properly capturing the spatial and temporal nature of temperature within the basin (temperature lapse rate). This value is currently a constant, implying that regardless of the time of year, a constant temperature lapse rate between different elevations is assumed.

A solution to this problem is to create a “variable” lapse rate. The variable lapse rate changes seasonally along with other meteorological values. A variable lapse rate can be derived by finding the difference between two temperature records at significantly different elevations. The difference will need to be bound so that the value is not outside the bounds of 0.0 C/km and -6.5 C/km. Other reasonable approaches also include adjusting the precipitation interpolation scheme so that less precipitation falls as snow, adjusting the precipitation lapse rate and applying a scalar to the winter air temperature records.

The annual average hydrograph based on portions of the record show that DHSVM better simulates the basin hydrology for distinct periods, such as the warm phase of the Pacific Decadal Oscillation (1977 to present). Figures 2 and 3 below are the annual hydrographs for the PDO-cool and PDO-warm periods.

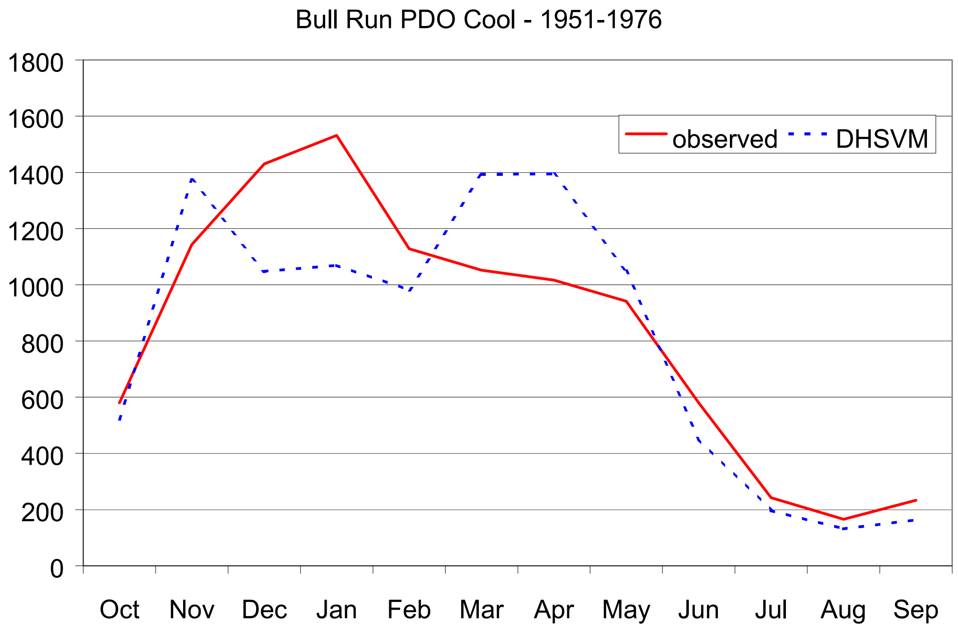


Figure 2. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO cool

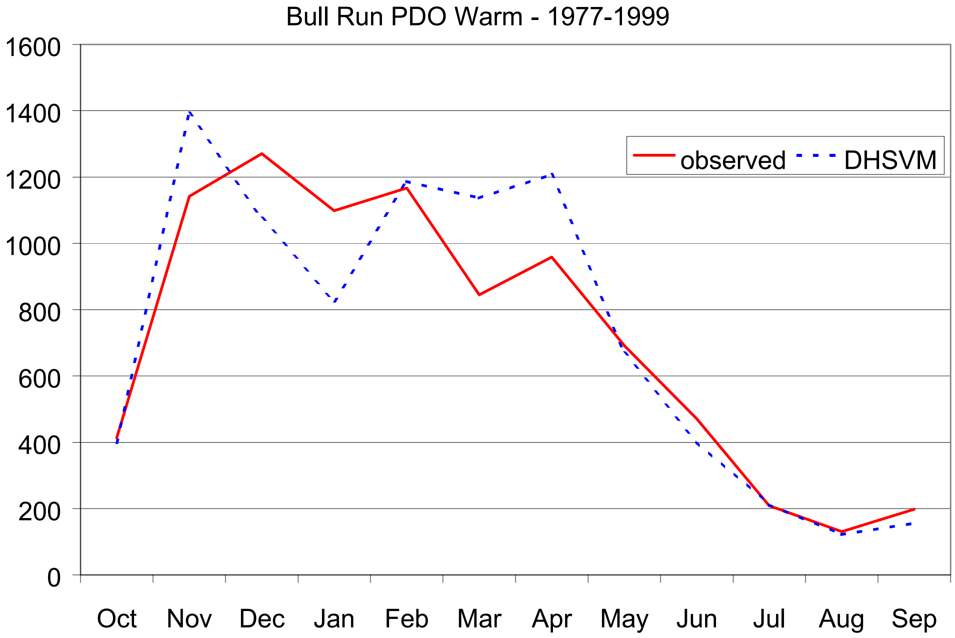
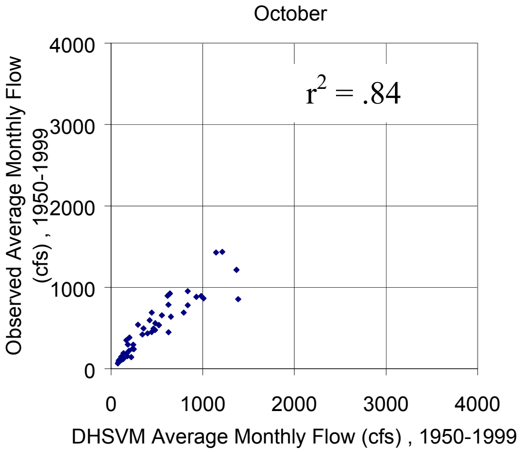
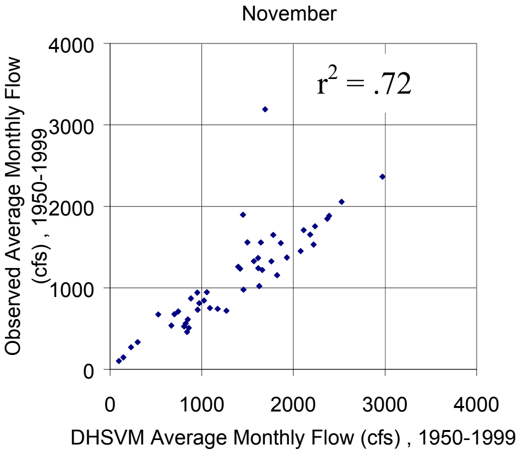


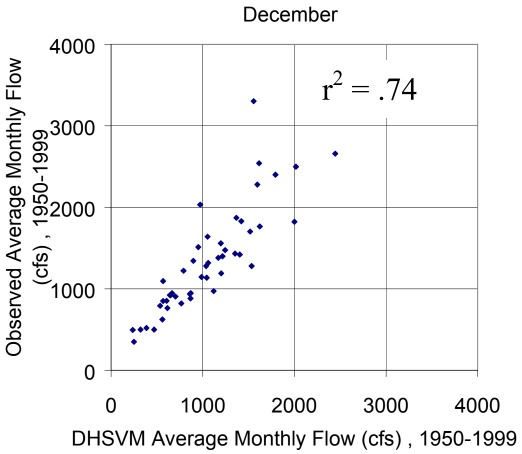
Figure 3. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO warm

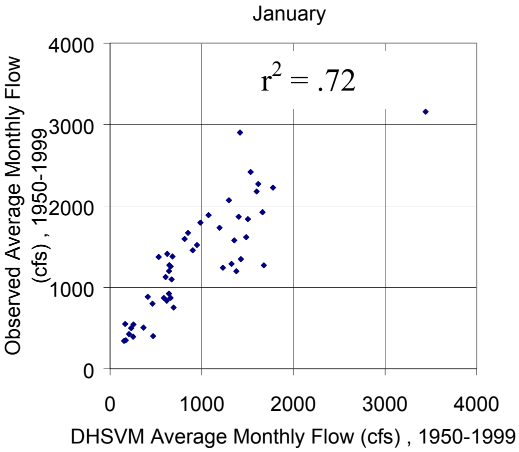
Seasonal Analysis

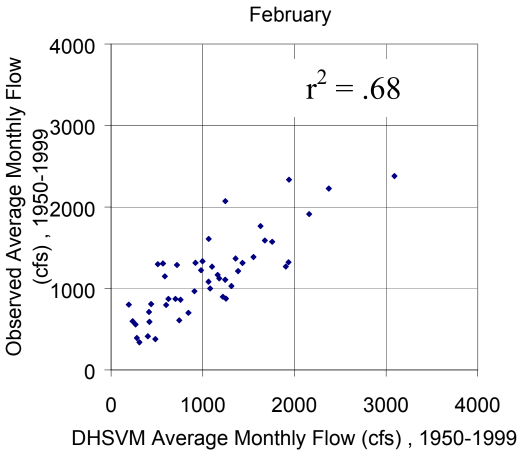
A monthly comparison of the observed and DHSVM flows for the 50 year record are shown in the twelve figures below. The r^2 values are indicated on the figures. Future calibration efforts will attempt to reduce the r^2 values.

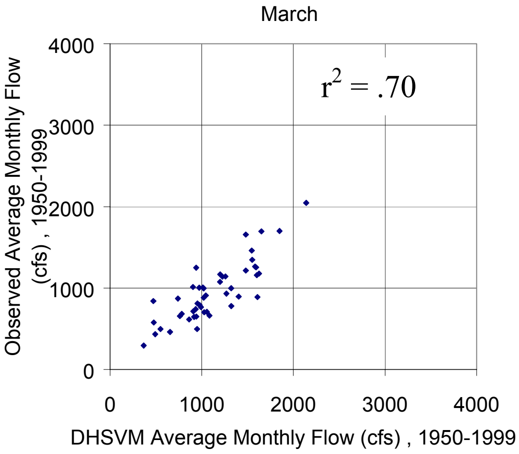

October
r^2 = .84
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

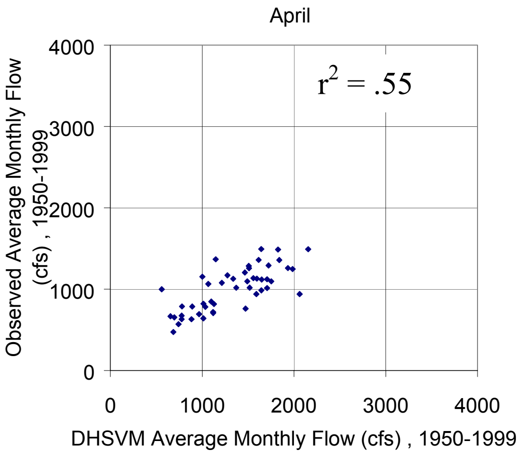

November
r^2 = .72
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

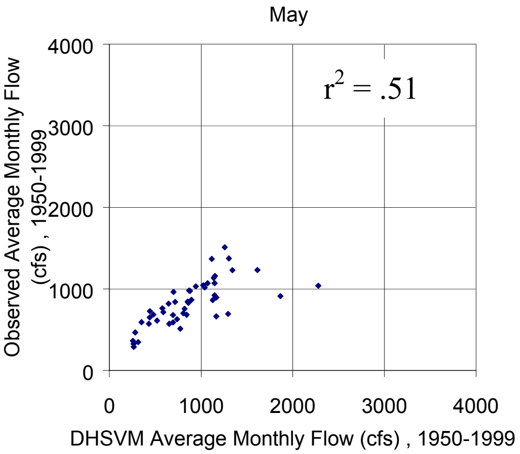

December
r^2 = .74
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

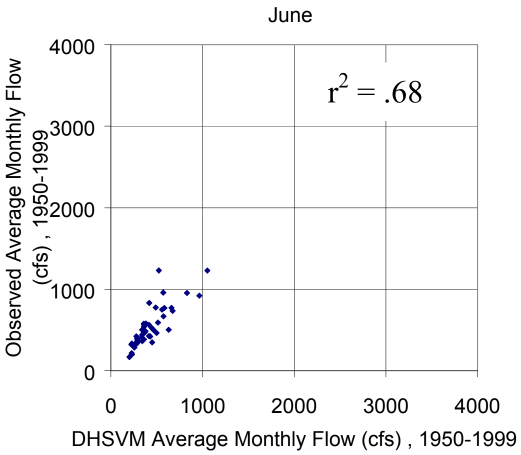

January
r^2 = .72
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

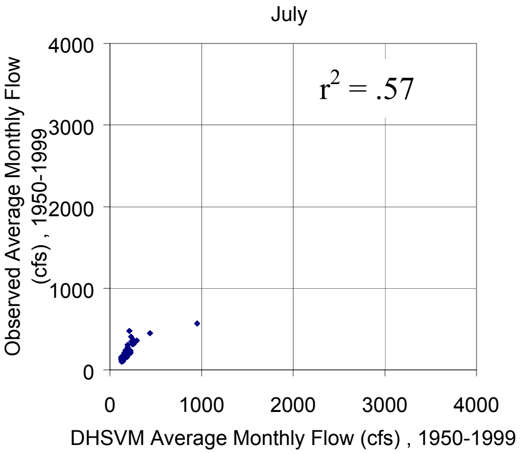

February
r^2 = .68
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

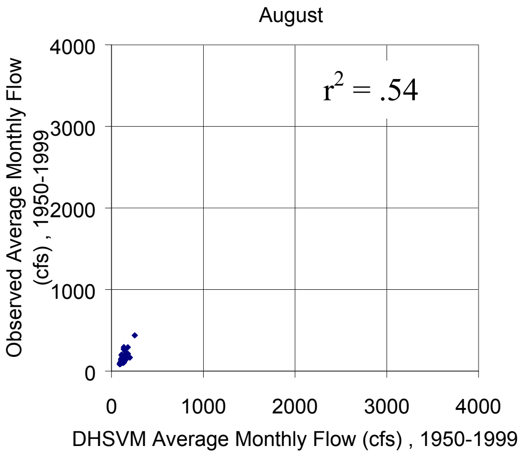

March
r^2 = .70
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

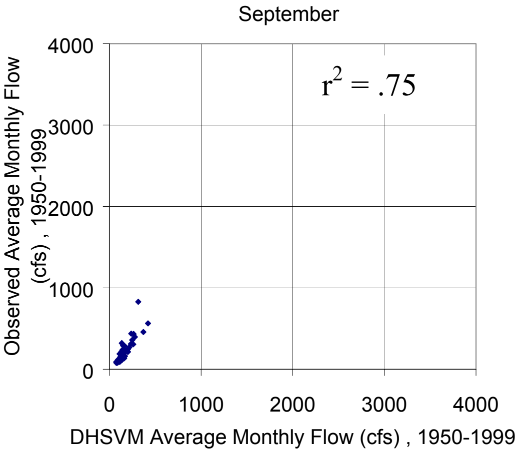

April
$r^2 = .55$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000


May
$r^2 = .51$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000


June
$r^2 = .68$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000


July
$r^2 = .57$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000


August
$r^2 = .54$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000


September
$r^2 = .75$
Observed Average Monthly Flow (cfs) , 1950-1999
DHSVM Average Monthly Flow (cfs) , 1950-1999
0
1000
2000
3000
4000

Summary

A great deal of progress has been made in developing the DHSVM model for the Bull Run system. The calibration has followed an extensive data collection process in which digital elevation maps, soil maps, vegetation maps, precipitation data, and streamflow data have been collected and incorporated in the DHSVM model. Annual water balances for the model look excellent, and the last challenge is capturing the volume and timing precipitation falling as snow and its later release as snow melt. This effort will be completed in the month of July.

University of Washington
Department of Civil and Environmental Engineering

TO: Joe Dvorak
FROM: Margaret Hahn and Richard Palmer
RE: DVSVM Calibration
DATE: June 11, 2001

This memo updates and replaces the memo of June 28, 2001 describing the DHSVM calibration process for the Bull Run Watershed.

Five model parameters have been adjusted in the DHSVM application:

> **Temperature Lapse Rate** interpolates temperature values in the basin according to elevation. The variable describes the change in temperature (degrees Celsius) per increase in meters of elevation. The variable is typically negative, implying that temperatures decrease as elevations increase. When the variable is made less negative, it reduces the amount of precipitation falling as snow at the basin's higher elevations.
>
> **Prism Maps** were removed from the DHSVM application. These spatial and statistically based precipitation maps interpolate precipitation within the basin. For the Bull Run watershed they underestimated the observed precipitation which, in turn, underestimated the precipitation in the model application. Precipitation in the basin is now interpolated in the basin with the Precipitation Lapse Rate.
>
> **Precipitation record** was returned to its original historical values. In previous calibrations, the precipitation portion of the meteorological record was scaled to compensate for the underestimation by the Prism maps.
>
> **Precipitation Lapse Rate** interpolates precipitation in the basin based on elevation. In previous calibrations this parameter was overridden by the use of the Prism maps.
>
> **Meteorological record** for this basin has been reduced to the one station that is located at Bull Run Headworks. The low elevation stations caused the interpolation algorithm to underestimate the precipitation in the basin.

The annual average hydrograph for the Bull Run Headworks (USGS 14138850) for the historical and newly calibrated DHSVM simulated data are given in Figure 1. The same graph is presented in Figure 2 with the old calibration values.

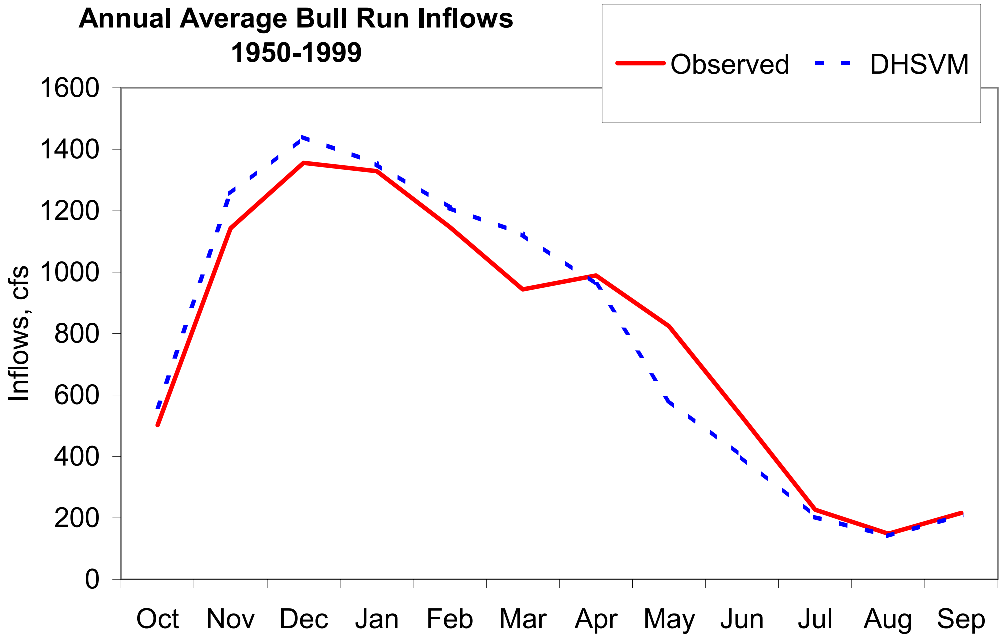


Figure 1. - Average Annual Hydrograph for the Bull Run at Headworks, 1950-1999, July 10 Calibration

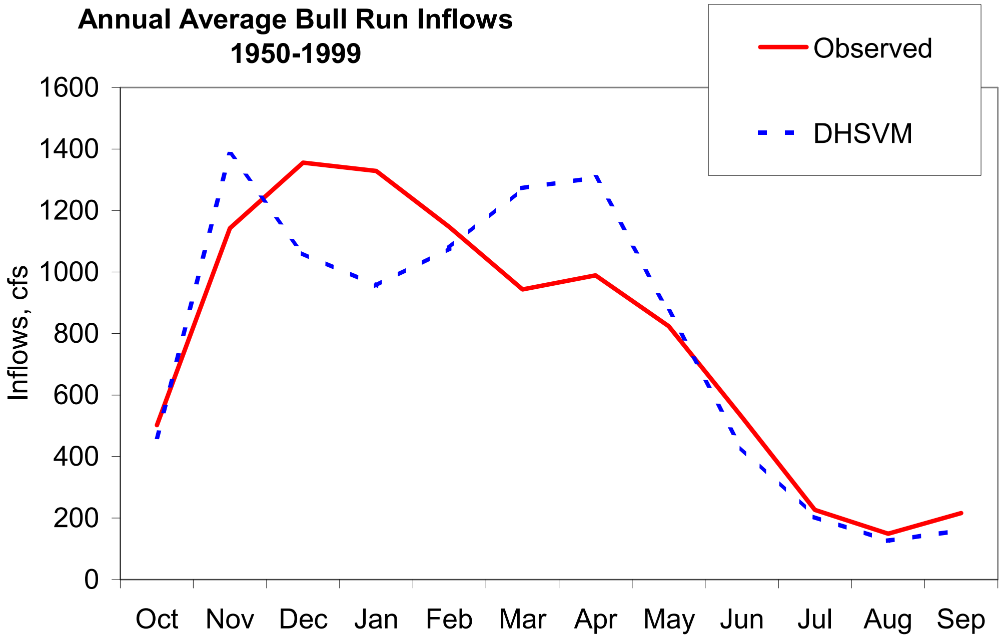


Figure 2. - Average Annual Hydrograph for the Bull Run at Headworks, 1950-1999, June 28 Calibration

The comparison of the two calibration results reveals the following:

~~1)~~5) The July 10 calibration is capturing the winter precipitation more accurately than the June 28 calibration.
~~2)~~6) The July 10 calibration stores less precipitation as snow in February and March. This results in an earlier recession curve throughout May and June.

The most significant change in the calibration is associated with the reduction of the temperature lapse rate from dry-adiabatic value of –0.006 ˚C/m to a saturated-adiabatic value of –0.003 ˚C/m. This variable will be further explored in the future by incorporating a variable lapse rate that is a function of precipitation. Two possible efforts include increasing the absolute value of the lapse rate for the February and March months or varying the lapse rate based on daily presence of precipitation.

The improvement in the model calibration is shown in the comparison of the hydrographs for distinct hydrologic periods, such as PDO-warm and PDO-cool. Previously the June 28 calibration showed that the DHSVM better simulates the basin hydrology for distinct periods, such as the warm phase of the Pacific Decadal Oscillation (1977 to present) (Figure 3 and 4). In the July 10 calibration, the model appears to closely simulate the observed record for both the PDO-cool and PDO-warm period.

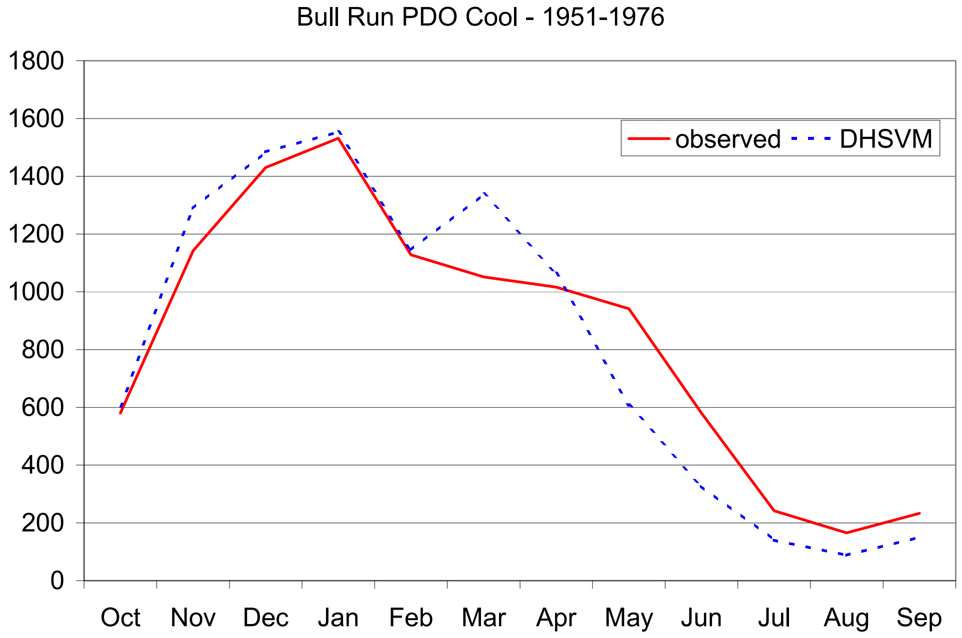


Figure 3. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO cool
July 10 Calibration

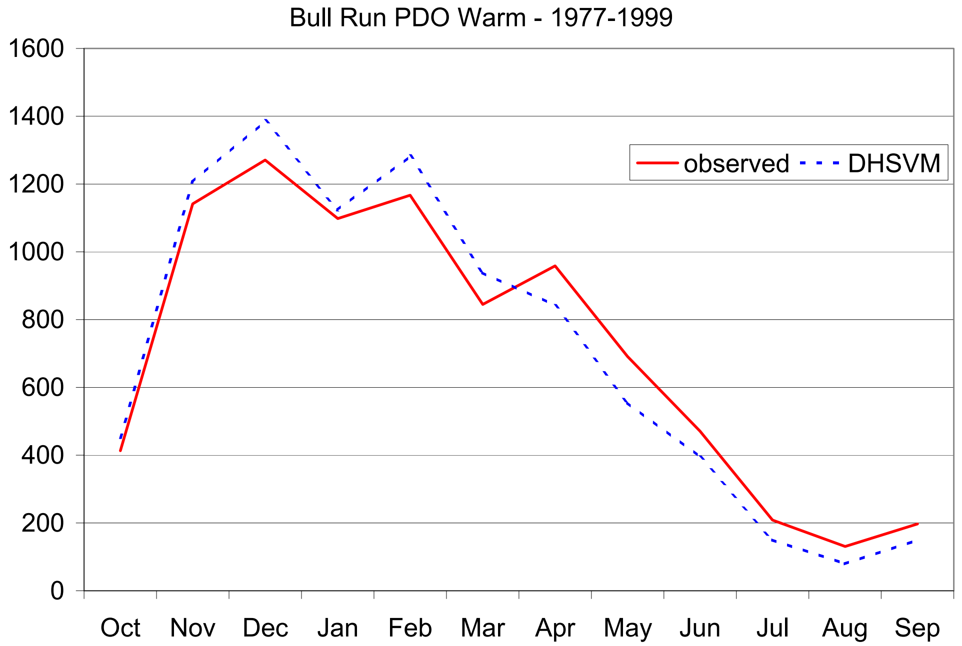


Figure 4. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO warm
July 10 Calibration

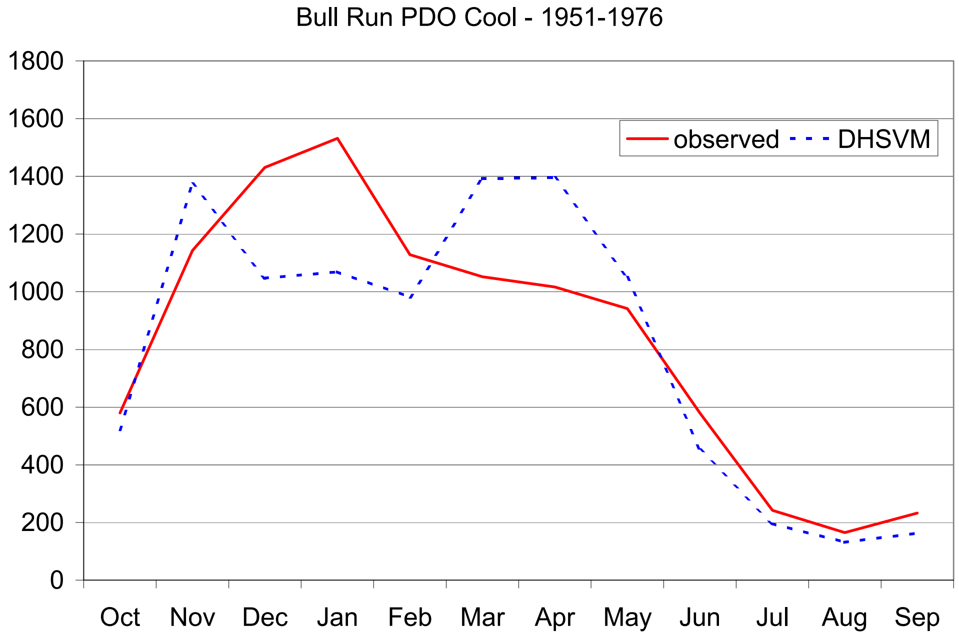


Figure 5. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO cool
June 28 Calibration

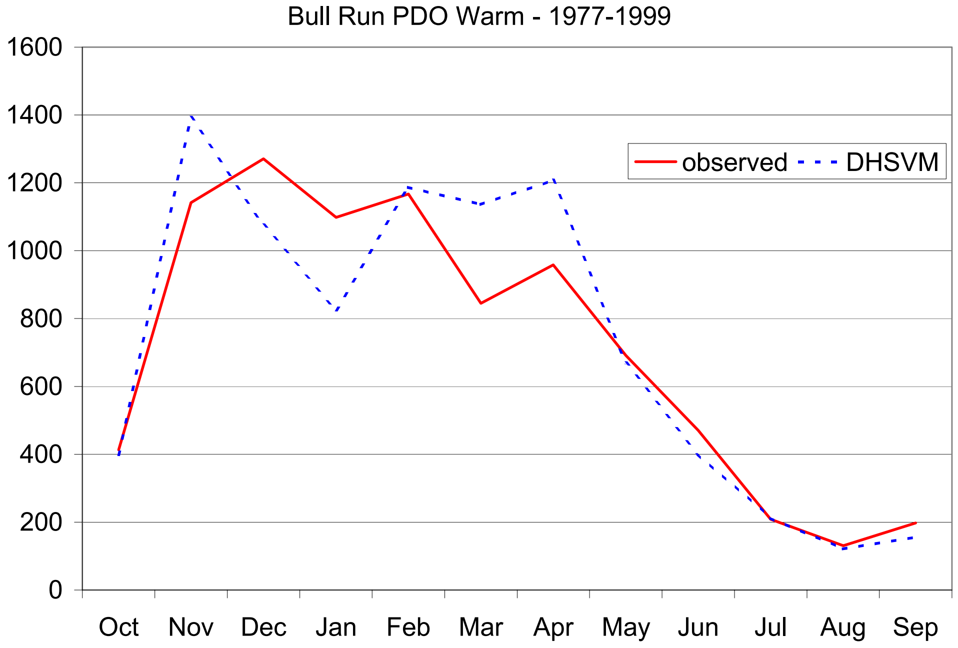
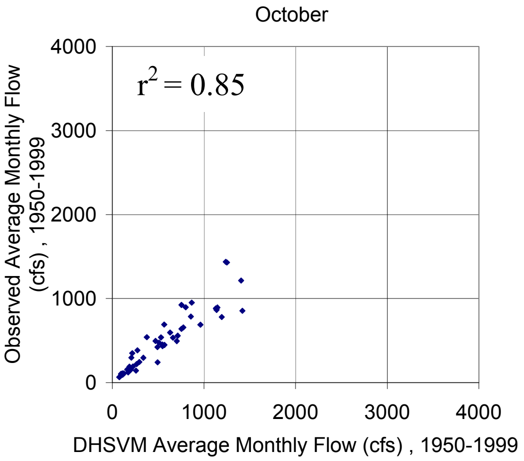


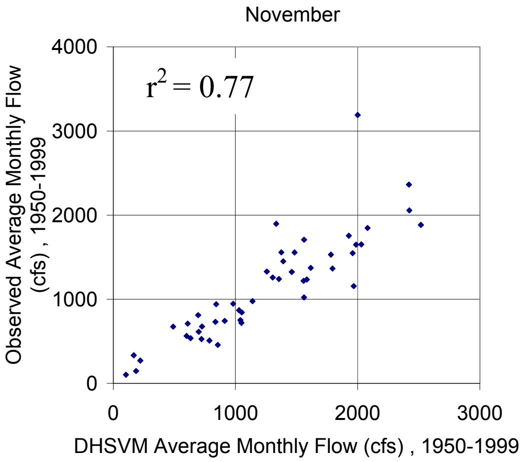
Figure 6. Annual Average Hydrograph for Bull Run at Bull Run Headworks, PDO warm
June 28 Calibration

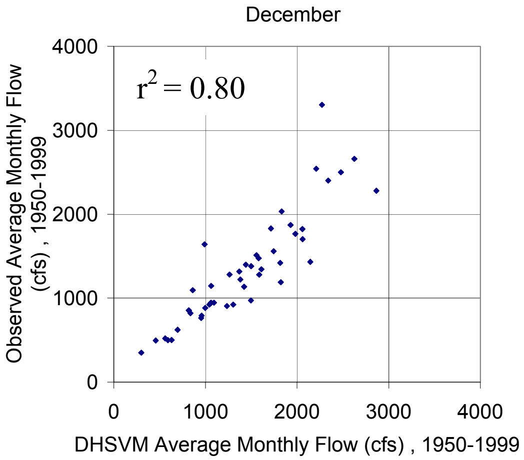
Seasonal Analysis

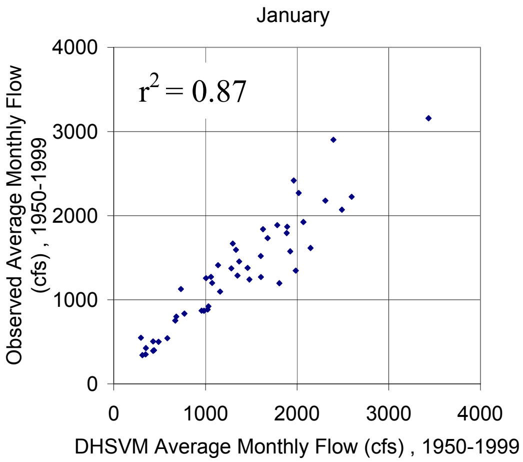
A monthly comparison of the observed and DHSVM flows for the 50 year record are shown in the twelve figures below. The r^2 values are indicated on the figures. A table comparing the r^2 values follows.

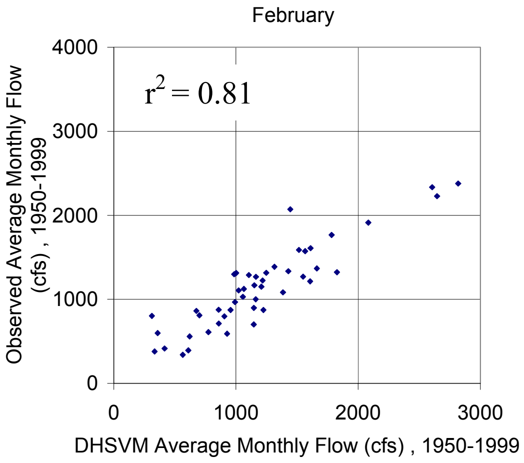
July 10 Calibration

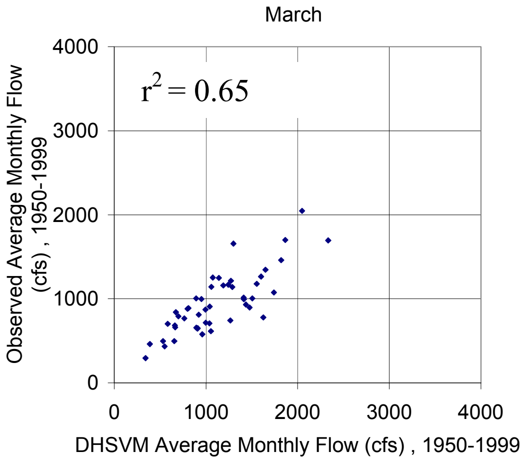

October


November

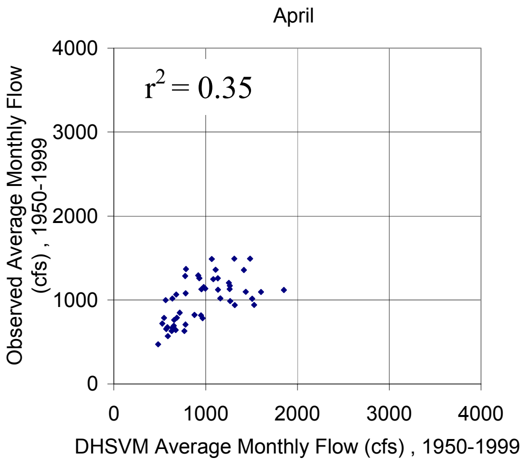

December

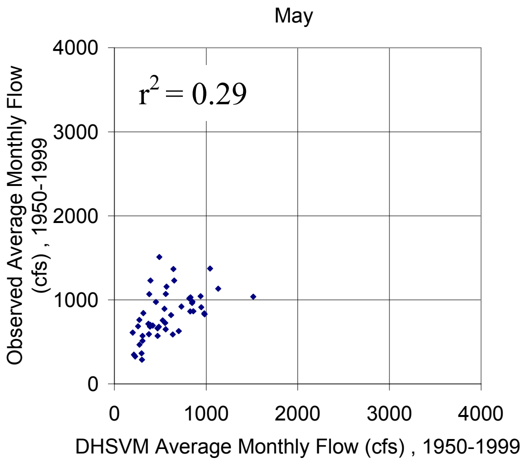

January

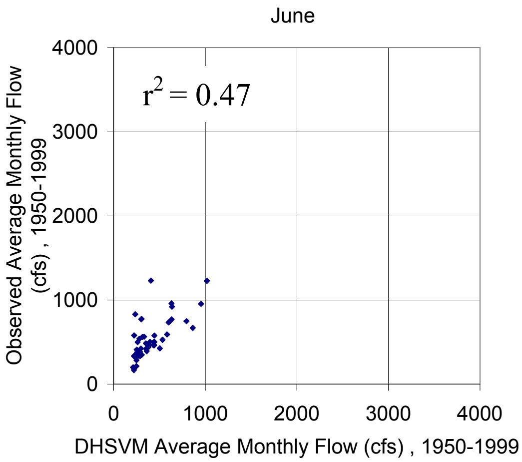

February

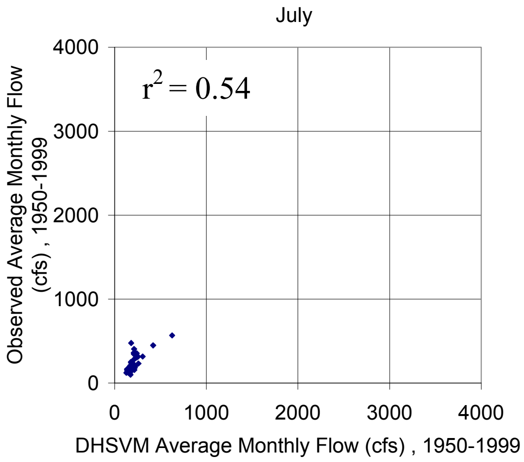

March

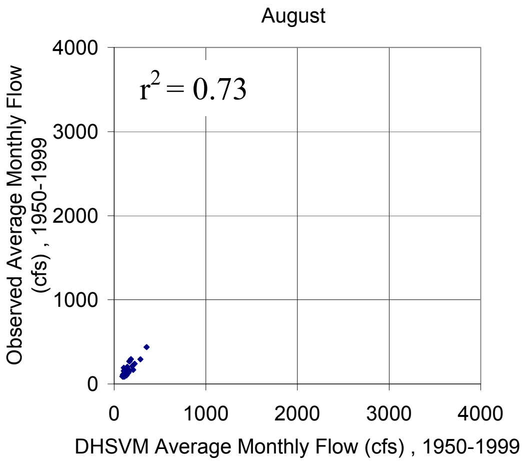
July 10 Calibration

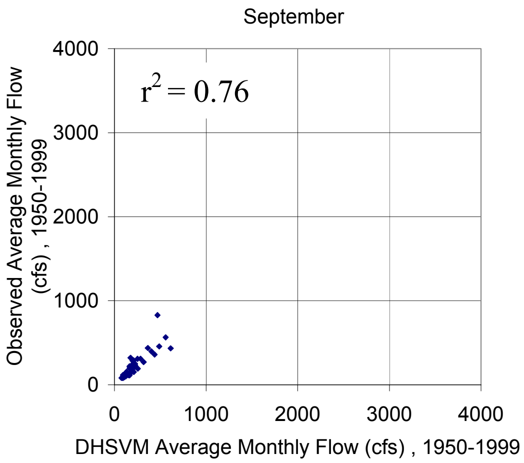




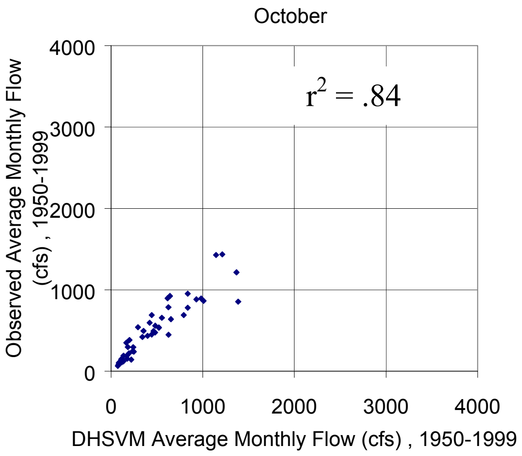


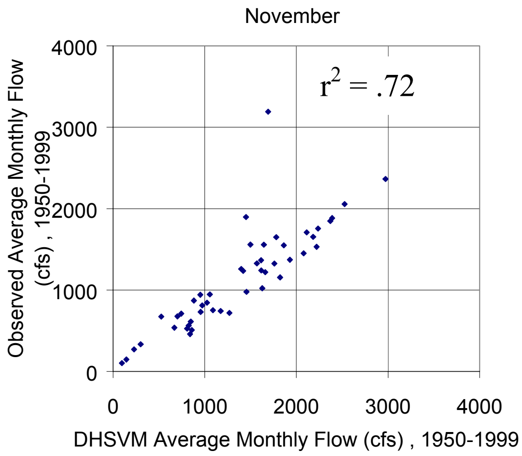


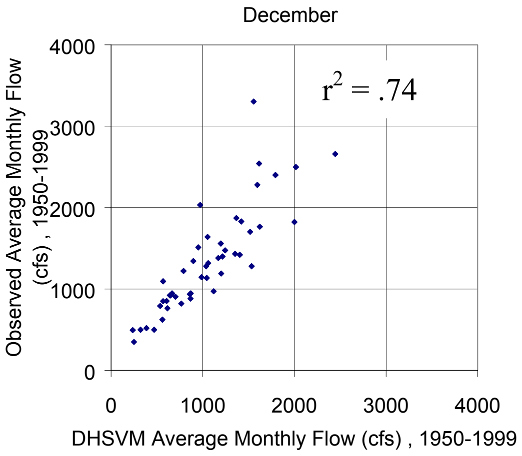


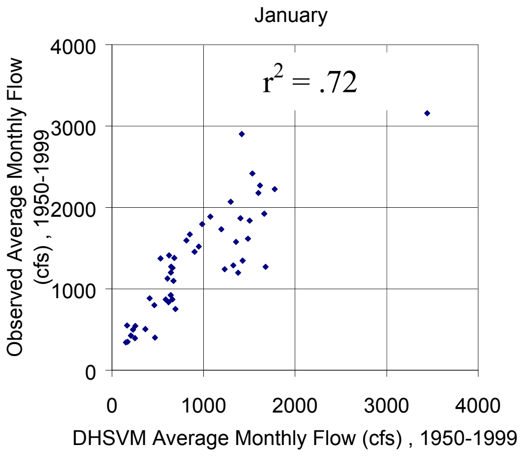


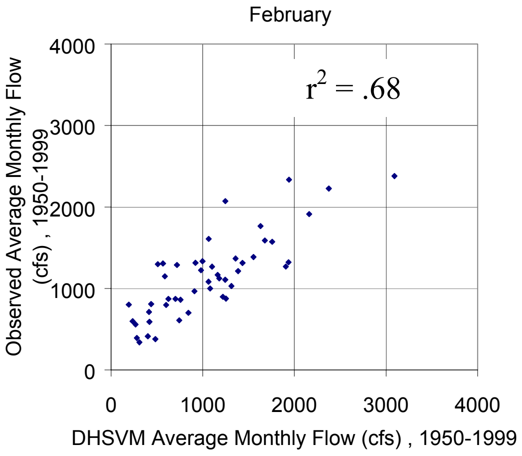
June 28 Calibration

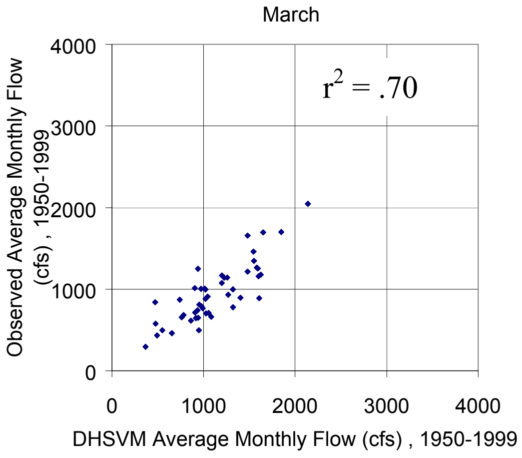




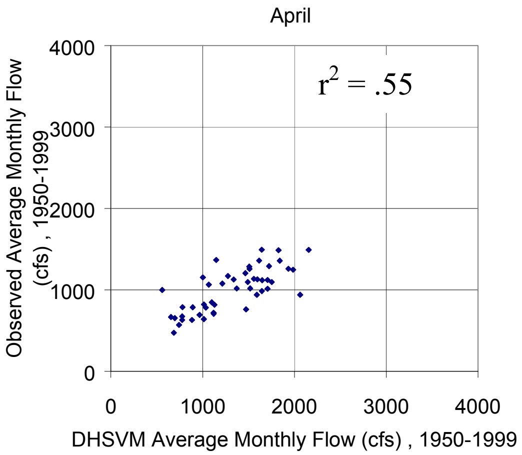


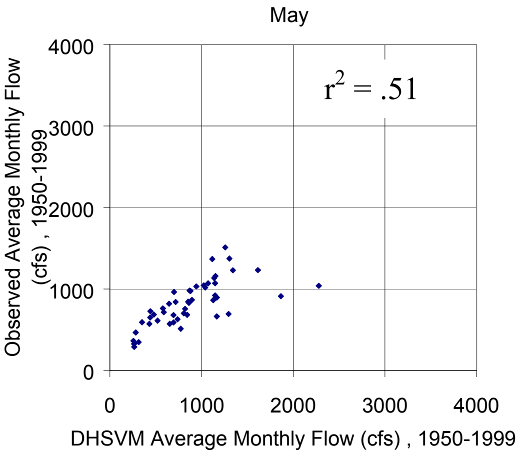


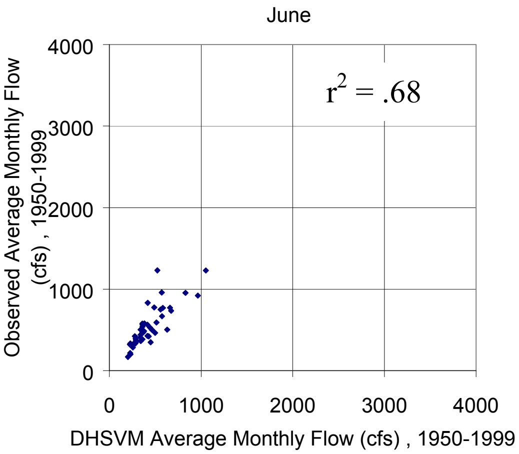


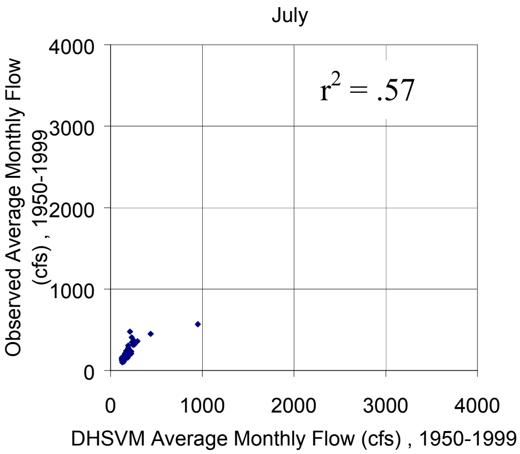


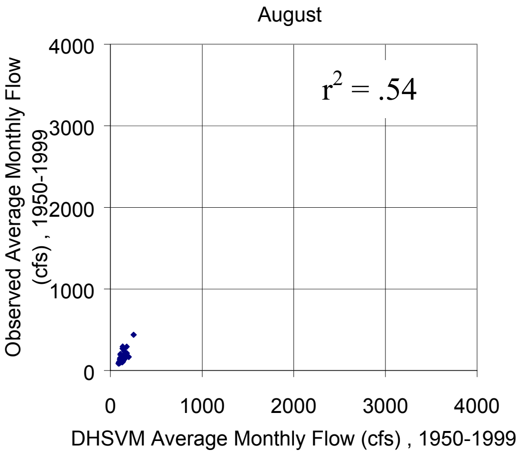
June 28 Calibration











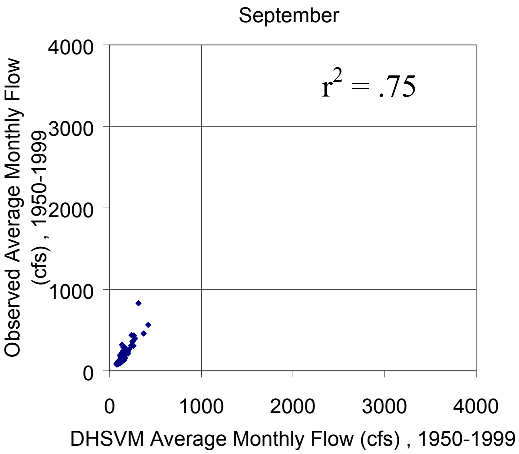


Table 1. r^2 values for the June 28th and the July 10th calibration efforts.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
June 28	0.72	0.68	0.70	0.55	0.51	0.68	0.57	0.54	0.75	0.84	0.72	0.74
July 10	0.87	0.81	0.65	0.35	0.29	0.47	0.54	0.73	0.76	0.85	0.77	0.80

The r^2 for the July 10th calibration are an improvement with the exception of the months March-July. This reinforces issues discussed previously concerning the timing of snow accumulation in March and April and the resulting change in ablation in May, June and July. Given this the r^2 test appears to be a reasonable metric in the model calibration efforts.

Summary

As indicated, future efforts will be placed on refining the variable lapse rate to ensure that the improvements in the r^2 values seen in August through February will also be seen in March through July. This work should be completed by the end of July.

Application and Calibration of the Distributed Hydrology-Soil-Vegetation Model of the Bull Run Watershed

1. *Background*

This report describes the application and calibration of the Distributed Hydrology-Soil-Vegetation Model (DHSVM) for the Bull Run watershed. The application and calibration is part of a larger effort that involves developing a precipitation/run-off model that is appropriate for evaluating the impacts of climate change in the watershed. This report includes a brief description of the DHSVM, a description of the DHSVM application to the Bull Run watershed, an outline of the calibration process and the calibration results.

2. *The Distributed Hydrology-Soil-Vegetation Model (DHSVM)*

DHSVM is a hydrological model developed in a collaborative effort between hydrologists at the University of Washington and the Battelle Memorial Institute. This model characterizes a watershed through a parameterization process and simulates a number of land surface processes explicitly. The spatial scale of this model is extremely high, with a pixel size of 150 meters by 150 meters. DHSVM has been successfully used to model a number of river basins in different areas of the PNW. DHSVM will be used to generate the streamflows associated with climate change in later stages of this research. It is currently being used at the University of Washington to generate short-term streamflow and snowpack forecasts for basins along the western slopes of the Cascade Mountain range (http://hydromet.atmos.washington.edu/).

With its explicit simulation of fine-scale hydrologic processes, the model is very effective for simulating the hydrologic response of small-scale catchments with complex topography. The model is structured as a grid with each pixel in the grid represented by a two-layer canopy model for evapotranspiration, a multi-layer unsaturated soil model and a saturated subsurface flow model. DHSVM's input includes temperature, precipitation, wind, humidity and incoming short- and long-wave radiation. A digital elevation dataset of the watershed is used to represent the topographical influences on the meteorological inputs and the movement of water from pixel to pixel. The model outputs include runoff, snow and snowmelt, soil moisture and evapotranspiration, and streamflow (Wigmosta 1994, Storck 2000, Hahn et al. 2001).

3. *Applying DHSVM to the Bull Run Watershed*

Each DHSVM application is based on a series of data sets and model parameters that describe a watershed. The data sets represent the general physical nature of the basin (elevation, soil type, precipitation, vegetation) and the parameters represent more detailed characteristics of interactions (roughness of snow, leaf area index, etc.) between the physical components of the basin. Both the data sets and the model parameters are described below.

Data sets

Elevation

A Digital Elevation Model (DEM) of the basin at a 150 meter horizontal resolution was obtained from merging 25 USGS quadrangle maps (10 meter horizontal resolution based on 1:240000 USGS topographic quads).

Basin Delineation and Stream Network Derivation

The contributing area above the confluence of the Bull Run River and the Little Sandy River was obtained based on the 150 meter DEM data set. A streamflow network was created assuming that a stream channel begins when the contributing area above a pixel (the combined area above a pixel that drains to it) exceeds 0.25 km^2. Five control points were defined for the stream network to provide streamflow output. The replication of the DHSVM control point contributing area to that of the USGS analysis of the basin is shown for each of the control points in Table 1.

Table 1. DHSVM basin areas and streamflow locations.

USGS #	**Name**	**USGS basin area km^2**	**DHSVM basin area in km^2**
14138850	Bull Run Reservoir Inflow	124.1	124.7
14138870	Fir Creek	14.1	14.7
14138900	North Forth Bull Run	21.5	21.2
14139800	South Fork Bull Run	39.9	39.5
14141500	Little Sandy	57.8	58.7

Soil Texture Class

Data on the USDA soil texture class (e.g. Sandy Loam, Silty Clay) for the Bull Run application were obtained from the USDA STATSGO Soils Database for the Conterminous US. Raw data are at a horizontal resolution of 1 km and contain information on as many as 13 different vertical soil layers. These data were aggregated vertically to obtain the dominant soil texture class in each 1 km pixel and disaggregated to a horizontal resolution of 150 meters to coincide with the Bull Run base DEM. The dominant soil classification in the Bull Run watershed is classified as Loam and is described by the following soil texture class parameters: lateral conductivity, conductivity exponential decrease with depth, maximum infiltration, surface albedo, number of soil layers, porosity, pore size distribution, bubbling pressure, field capacity, wilting point, bulk density, vertical conductivity, thermal conductivity, and thermal capacity.

Soil Depth

Accurate data on the distribution of soil depth over a watershed is often unavailable. This is the case for the Bull Run watershed. Therefore, an algorithm that estimates the soil depth over the basin based on slope, upstream contributing area and elevation was used. This approach was also used in setting up the University of Washington PRISM (Puget Sound Regional Synthesis Model) modeling system of the Puget Sound basins (http://www.prism.washington.edu/lc/PSARRM/).

Vegetation

The distribution of vegetation over the Bull Run watershed was created from a LandSat™ image provided by the Portland Water Bureau and contains information on the recovery of recently harvested areas in the watershed. Thirty meter resolution data were aggregated to a 150 meter resolution. The Bull Run watershed is described by eight vegetation classifications: Mixed Forest (4%), Grassland (3%), Cropland (2%), Water (2%), Confier Late Seral (59%), Conifer Mid Seral (17%) and Conifer Early Seral (13%). Each vegetation classification is described by the following parameters: impervious fraction, overstory present, understory present, fractional coverage, trunk space, aerodynamic attenuation, radiation attenuation, maximum snow interception capacity, snow interception efficiency, mass release snow drip ratio, height, summer leaf area index, winter leaf area index, maximum wind resistance, minimum wind resistance, moisture threshold, vapor pressure, albedo, number of root zones, root zone depths, overstory root fraction, and understory root fraction.

Terrain Shading and Sky View Maps

DHSVM contains the option to apply topographic controls on incoming direct and diffuse shortwave radiation. These terrain maps describe the combination of slope, aspect and terrain shadows for the midpoint for each timestep of a typical day for each month of the year. Sky view maps provide information about the amount of sky visible from each model pixel.

PRISM Precipitation Maps

DHSVM contains the option to distribute point (i.e. station) observations of precipitation over the watershed using the Oregon State University PRISM precipitation climatology. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) precipitation climatology has spatial and statistical precipitation maps that use point observations and digital elevation models to interpolate precipitation vertical and horizontally across basin. The interpolation scheme involves a simple linear regression equation and a series of interpolation weights that characterize each observation station used in the interpolation. The weights are distance, elevation, cluster, vertical layer, topographic effect, coastal proximity, and effective terrain. For example, the observation data is less emphasized if it is relatively far vertically or horizontally from the target grid cell whose precipitation is being estimated (Daly 1994).

Meteorological records

The Bull Run DHSVM has eight meteorological stations available to interpolate values precipitation, temperature, humidity, long and short-wave radiation and wind throughout the basin. These time series data sets range from October 1949 to July 2000. The observation stations have the following locations: Bonneville, Estacada, Forest Grove, Hillsboro, Bull Run Headworks, Oregon City, Portland Airport and Three Lynx. Only the Bull Run Headworks meteorological station is located within the watershed. Also, it is the highest elevation observation station.

Model Parameters

Several basin wide parameters are used in performing the snow accumulation and ablation calculations. These values are most often constant for the entire watershed with the exception of the temperature and precipitation lapse rates, which can vary temporally (monthly or daily).

Ground Roughness – Roughness of soil surface (m).
Snow Roughness – Roughness of snow surface (m).
Rain Threshold – Minimum temperature at which rain occurs (C).
Snow Threshold – Maximum temperature at which snow occurs.
Snow Water Capacity – Snow liquid water holding capacity.
Reference Height - (Wind) Reference height.
Rain LAI Multiplier – Leaf Area Index multiplier for rain interception.
Snow LAI Multiplier – Leaf Area Index multiplier for snow interception.
Min Intercepted Snow – Intercepted snow that can only be melted.
Temperature Lapse Rate – Temperature lapse rate (C/m).
Precipitation Lapse Rate – Precipitation lapse rate (C/m).

4. Calibration

The DHSVM application has been calibrated in three stages: 1) Initial Calibration, 2) Data Set Driven Calibration and 3) Parameter Driven Calibration. Each effort is described below. This three-stage process is typical in calibrating physical models. It is important to first establish that the basic model is appropriate, apply specific data for a basin, and then modify parameter values to obtain a best fit.

Initial Calibration

The initial calibration was based solely on regional or watershed data sets such as those for soil, vegetation, elevation, and precipitation records. The results of this calibration effort are summarized in Figure 1 and 2 for the 1981 water year.

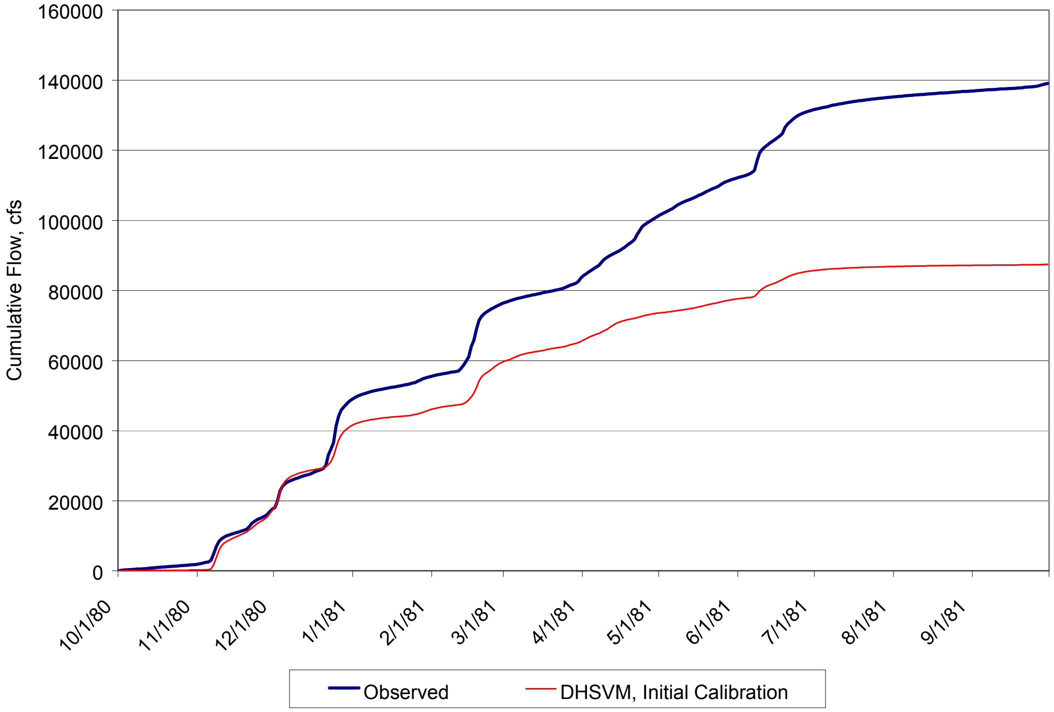


Figure 1. Initial Calibration, Bull Run Mainstem– Cumulative Flows

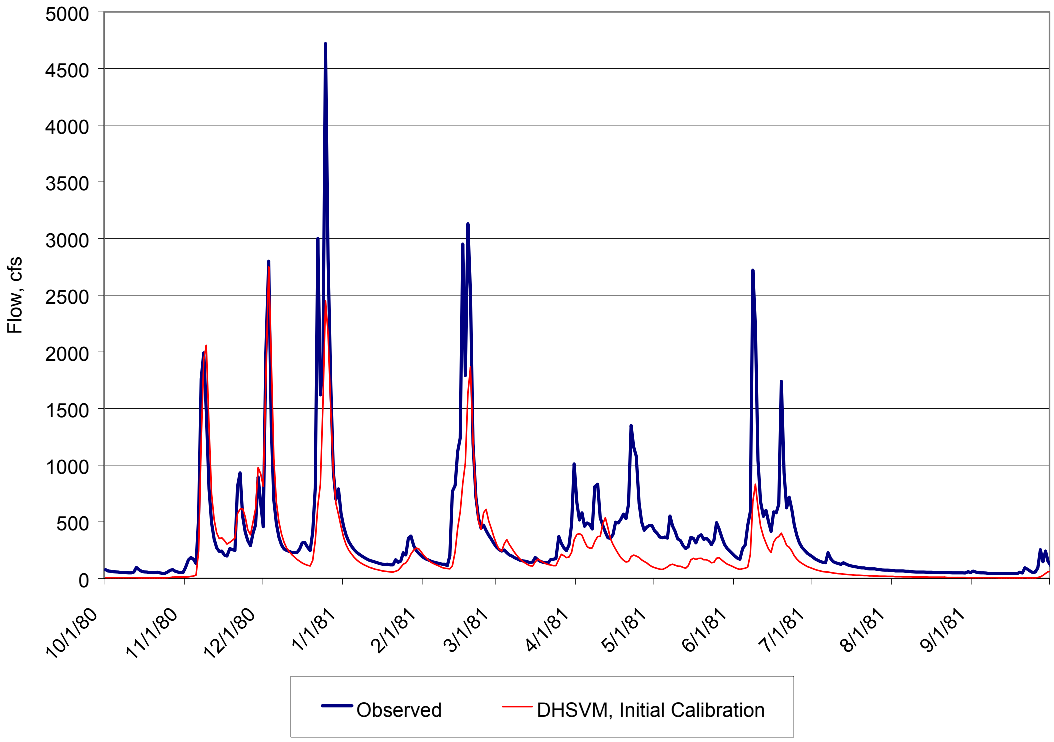


Figure 2. Initial Calibration Results, Bull Run Mainstem Flow Comparison

Figure 1 indicates that DHSVM initially underestimates the annual flows in the Bull Run. In particular, the initial calibration underestimates the low summer flows, Figure 2. These observations helped in the second iteration of the model calibration.

Data Set Driven Calibration

The data sets targeted for the second calibration included the soil depth, vegetation and the precipitation. Sensitivity analyses were performed on the data sets and the variables that define them.

Soil Depth - Given that the model does not explicitly calculate groundwater, the soil depth data set was altered to increase the amount of summer return flow, allowing the lower layers of soil to store infiltrated water as groundwater. Changing the soil depth improved the simulation of the summer low flows.

Vegetation - The Leaf Area Index, which is used in calculations to estimate evaporation and canopy snow accumulation and snowmelt was adjusted for the predominant vegetation type in the basin. The LAI values used to describe the different types of vegetation in the model are based on general values and are not basin specific. Changing these values gave a slight improvement to the overall water balance.

Precipitation - Changing the precipitation in the basin gave the greatest improvement in the simulated water balance. Two models are appropriate for incorporating precipitation information into DHSVM: 1) using a series of meteorological observation stations and interpolating the precipitation across the basin using the Oregon State University PRISM climatology maps and 2) using a precipitation lapse rate value that interpolates precipitation across the basin based on the elevation (i.e., an increase in precipitation in meters for an elevation gain in meters). The Data Set Driven Calibration uses the PRISM based precipitation model.

The precipitation in the Bull Run watershed was initially underestimated for two reasons, a lack of a long-term observations for the basin’s higher elevations and a statistical bias in the PRISM maps that underestimates the amount of precipitation at the watershed's higher elevations. To account for this combined underestimation, the actual precipitation records were increased by 20%.

The calibration of the model for this second effort is shown in Figures 3 and 4. These figures also show the bias correction applied to the summer low flows.

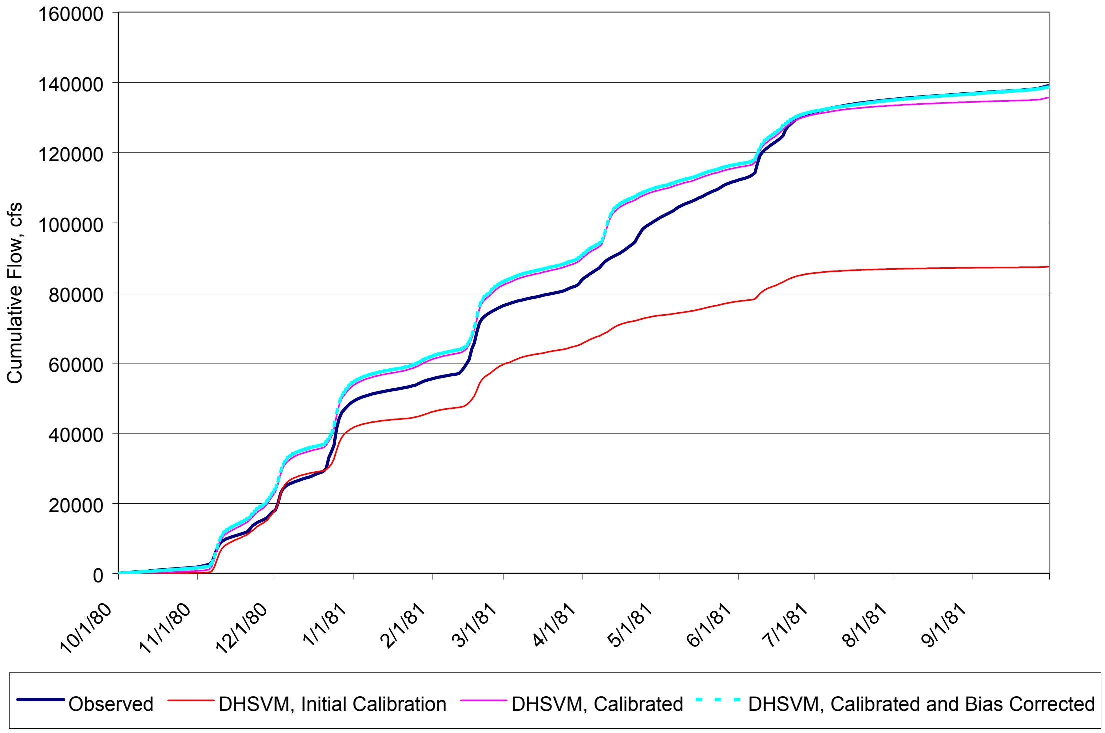


Figure 3. Data Set Driven Calibration Results for Bull Run Mainstem, 1981 cumulative flows

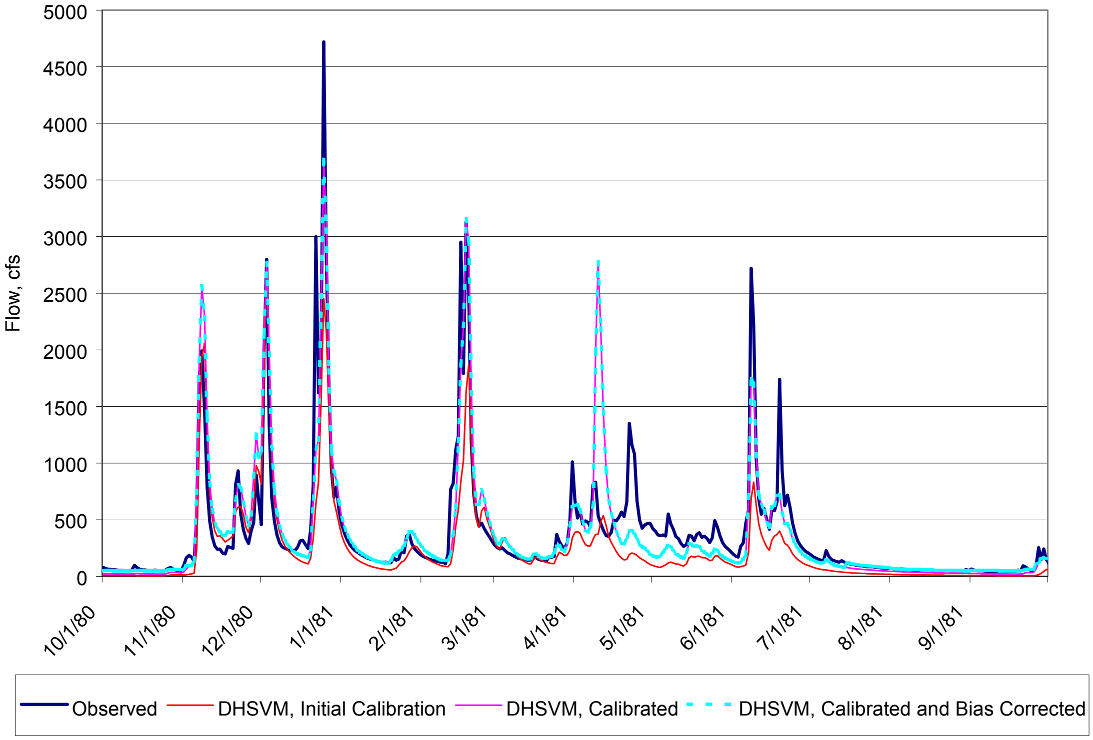


Figure 4. Data Set Driven Calibration Results for Bull Run Mainstem, 1981 hydrograph

Although the annual cumulative flows and the time series flow comparisons improved for the Data Set Driven Calibration, the average monthly hydrograph for the simulated flows from DHSVM were not realistic and did not match the observed average annual hydrograph (Figure 5). The difference in the average annual hydrographs indicate that the model is overestimating the amount of precipitation that falls as snow, resulting in lower than expected flows in the winter and higher snow-melt based spring flows. It is important the accumulation and melt of snow in the watershed is modeled sufficiently so that the model can be used to measure the shift in snow hydrology associated with climate change. This difference in the average annual hydrograph between the Data Set Driven Calibration and the observed record encourages the efforts of the third calibration based on model parameters.

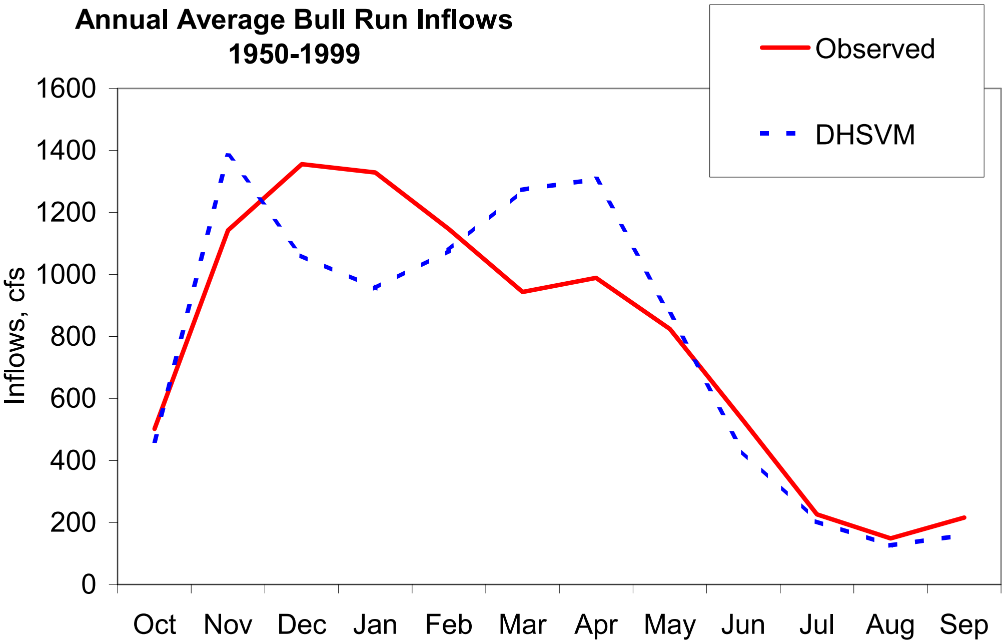


Figure 5. Data Set Driven Calibration,
Annual Average Bull Run Inflow Hydrograph, 1950-1999

Parameter Driven Calibration

The third and final DHSVM calibration focused matching the observed and simulated flows for the average annual hydrograph and the annual cumulative flows. Values changed in the model include the temperature lapse rate and an alternative method for interpolating the precipitation across the basin. These values and parameters are described below in more detail.

Temperature Lapse Rate interpolates temperature values in the basin according to elevation. Temperature lapse rates are typically negative, for instance, -0.006 C°/meter elevation. An increase in this variable, degrees Celsius per meter elevation, reduces the amount of precipitation falling as snow at the basin's higher elevations. Several sensitivity analyses were performed with this parameter by changing the constant value and by varying the value on a monthly basis.

Prism Maps were removed from the DHSVM application. These spatial and statistically based precipitation maps were used to interpolate precipitation within the basin and underestimated the observed precipitation, which in turn underestimated the precipitation in the model application. Precipitation in the basin is now interpolated in the basin with the precipitation lapse rate, rather than the PRISM maps.

Precipitation record was returned to its original historical values. In previous calibrations, the precipitation portion of the meteorological record was scaled to compensate for the underestimation by the PRISM maps.

Precipitation Lapse Rate interpolates precipitation throughout the basin based on elevation. In previous calibrations this parameter was overridden by the use of the PRISM maps.

Meteorological record for this basin has been reduced to the one station that is located at Bull Run Headworks. The low elevation stations caused the interpolation algorithm to underestimate the precipitation in the basin.

Calibration Metrics

Several metrics show the improvement in the calibration of the DHSVM model, the average annual hydrograph, the r^2 values of monthly average flows, cumulative flows for the period of record (1950-1999) and on an annual basis, and a streamflow time series comparison for the period of record.

Average Annual Hydrograph

The Parameter Driven Calibration dramatically improved the average annual hydrograph (Figure 6 compared to Figure 5). The DHSVM is still slightly overestimating flows during the winter and underestimating the flows in the spring.

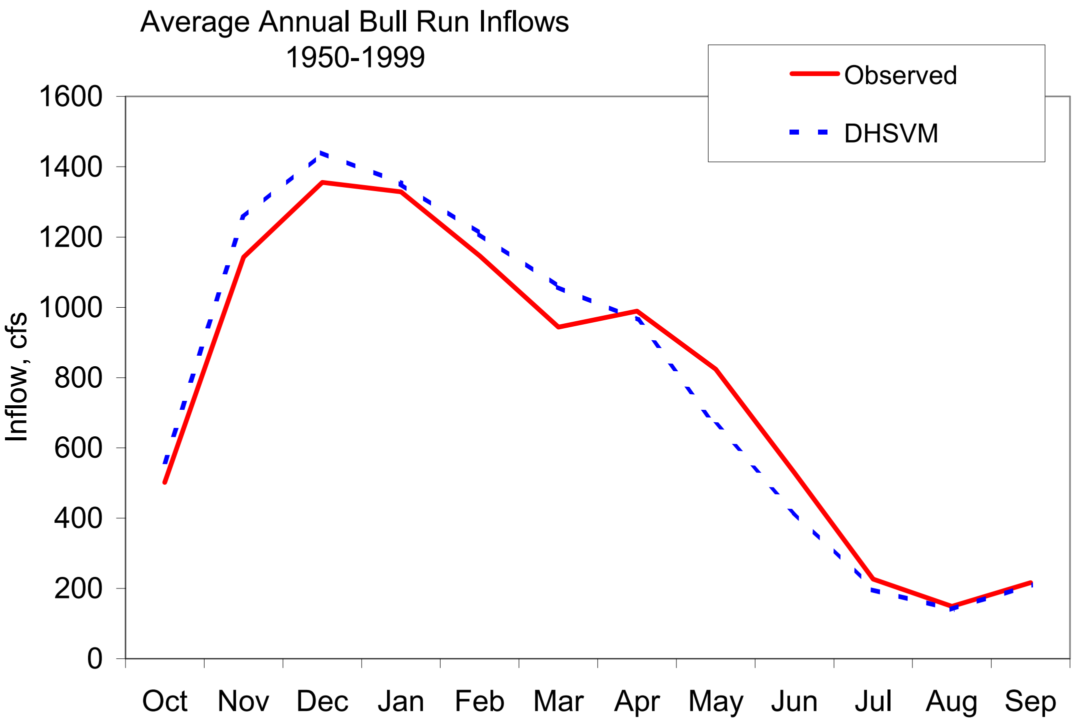


Figure 6. Parameter Driven Calibration,
Average Annual Bull Run Inflow Hydrograph, 1950-1999

Comparison of Monthly Flows

A comparison between the simulated and observed flows is also made on a monthly scale. Average monthly flows are calculated for each month of each year for both the simulated and observed flows and plotted against one another. Figure 7 shows a typical comparison.

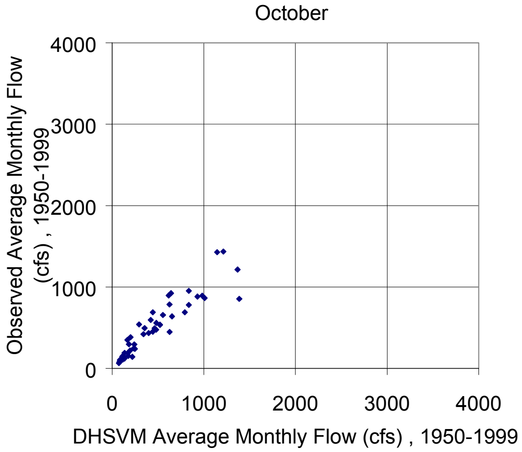


Figure 7. Annual Average Monthly Flows, DHSVM versus Observed

The r^2 values are calculated for each monthly comparison for the Data Set Drive and the Parameter Driven calibrations. These values are shown in Table 2 below. Also included in the table are the r^2 values associated with an intermediate calibration in the Parameter Driven calibration. The Intermediate Parameter Driven Calibration r^2 improves on those for the Data Driven Calibration values for the fall and winter months (August-February), but are less for the spring and summer months. The Final Parameter Driven Calibration r^2 values are an improvement on the Intermediate Parameter Driven Calibration values for the spring and summer months, but do not improve the April, May, and June r^2 values from the Data Driven Calibration.

Table 2. r^2 Values for Comparison between DHSVM Simulated and Observed Average Monthly Flows for Data Driven and Final Parameter Driven Calibration efforts.

Calibration	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Data Driven	0.72	0.68	0.70	0.55	0.51	0.68	0.57	0.54	0.75	0.84	0.72	0.74
Parameter Driven Intermediate	0.87	0.81	0.65	0.35	0.29	0.47	0.54	0.73	0.76	0.85	0.77	0.80
Parameter Driven Final	0.87	0.81	0.70	0.52	0.38	0.51	0.58	0.72	0.79	0.85	0.77	0.80

Cumulative Flows

The cumulative flow comparison, Figure 8, shows that for the period of record the water balance between the observed flows and DHSVM are very similar. The cumulative flows for each year (Figures 9-14) show that the model simulates the cumulative flow very accurately for many years in the period of record. Also, the model underestimates the cumulative flow for some years while it overestimates for others. There appears to be no consistent bias in the model results for which to correct.

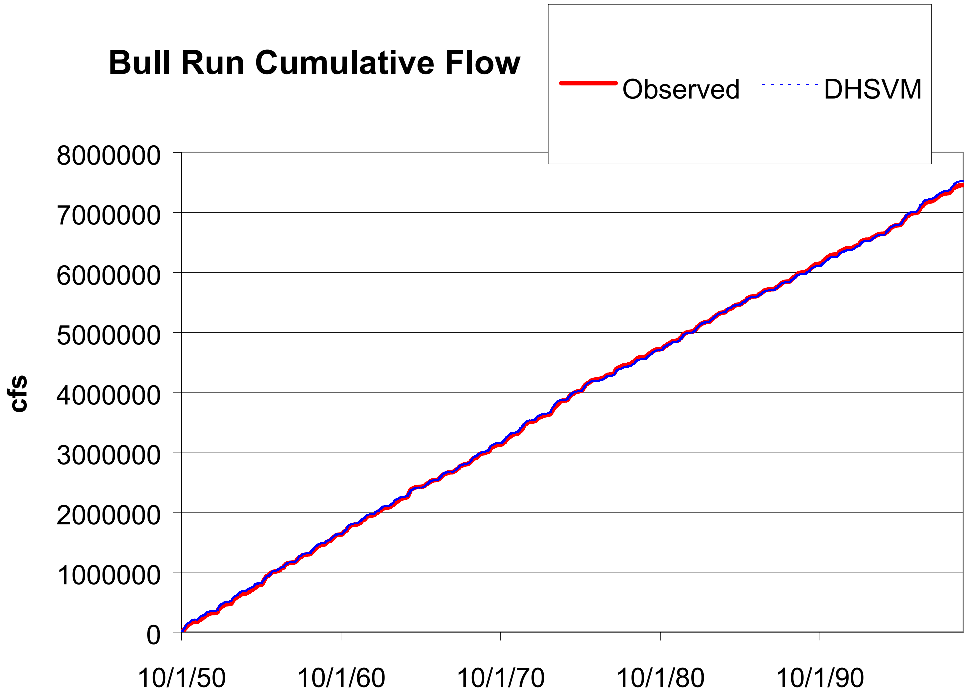


Figure 8. Parameter Driven Calibration,
Cumulative Flows, Bull Run Inflows into Dam 1, 1950-1999

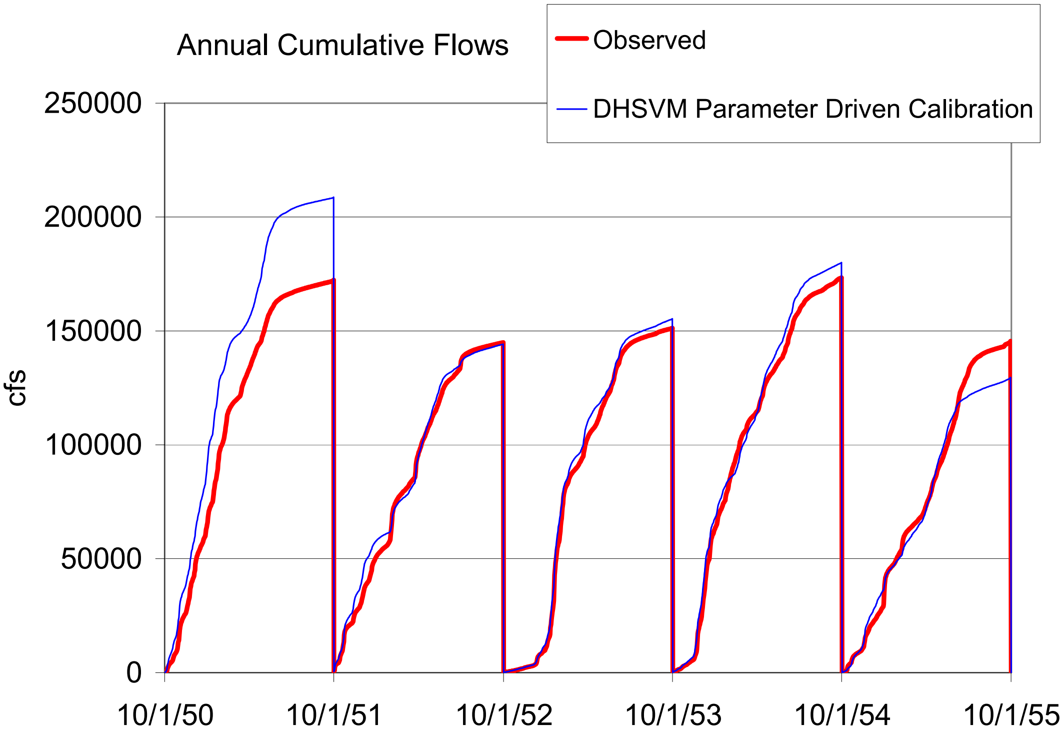


Figure 9. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1950-1955

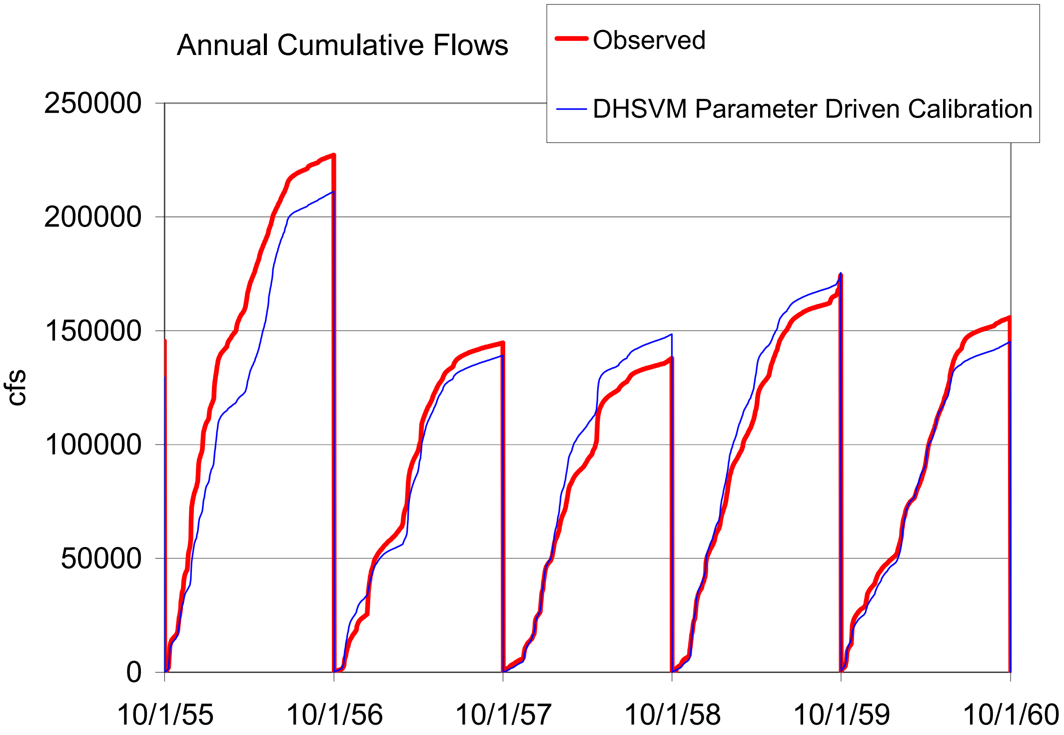


Figure 10. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1955-1960

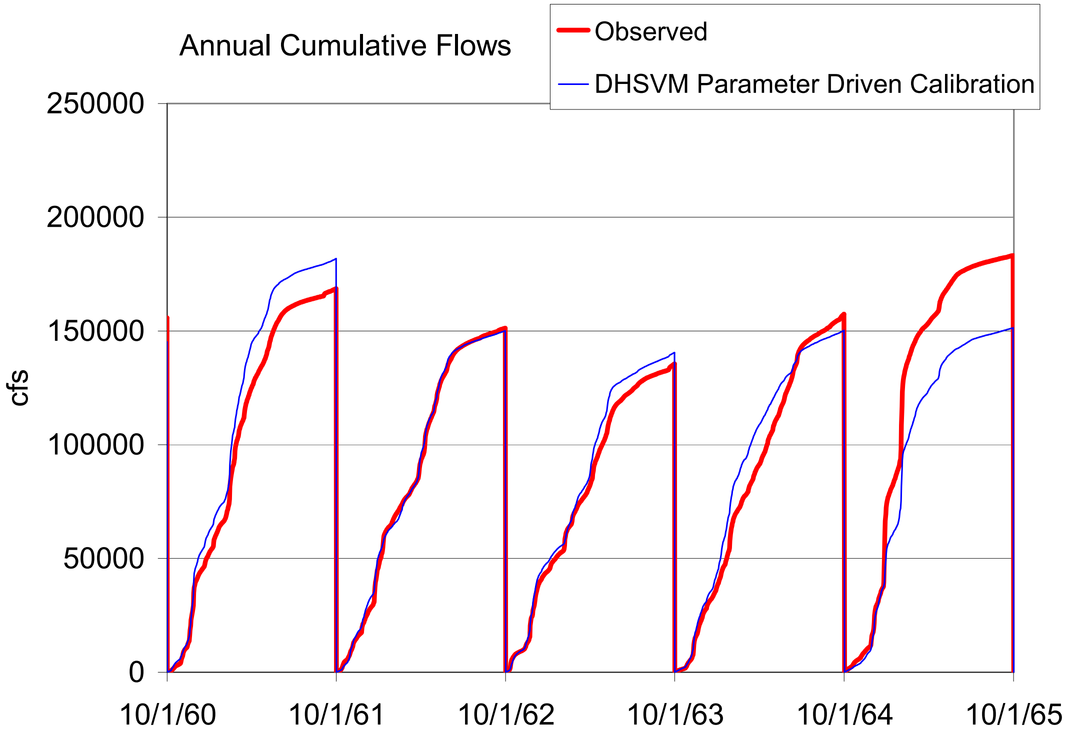


Figure 11. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1960-1965

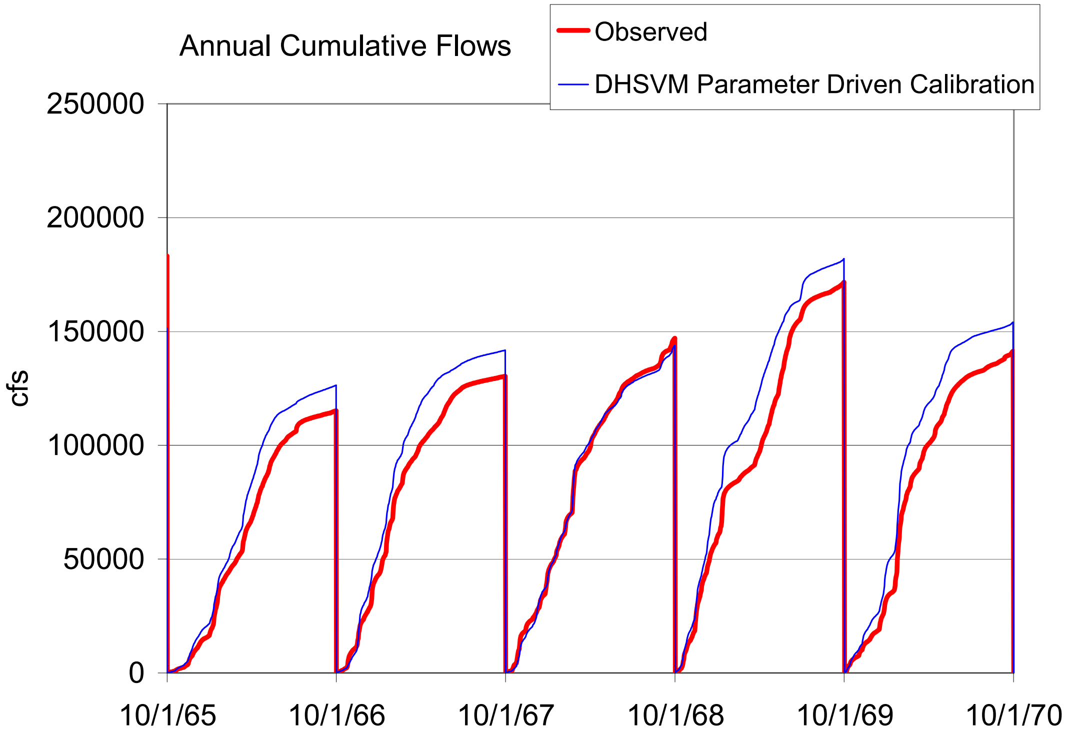


Figure 12. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1965-1970

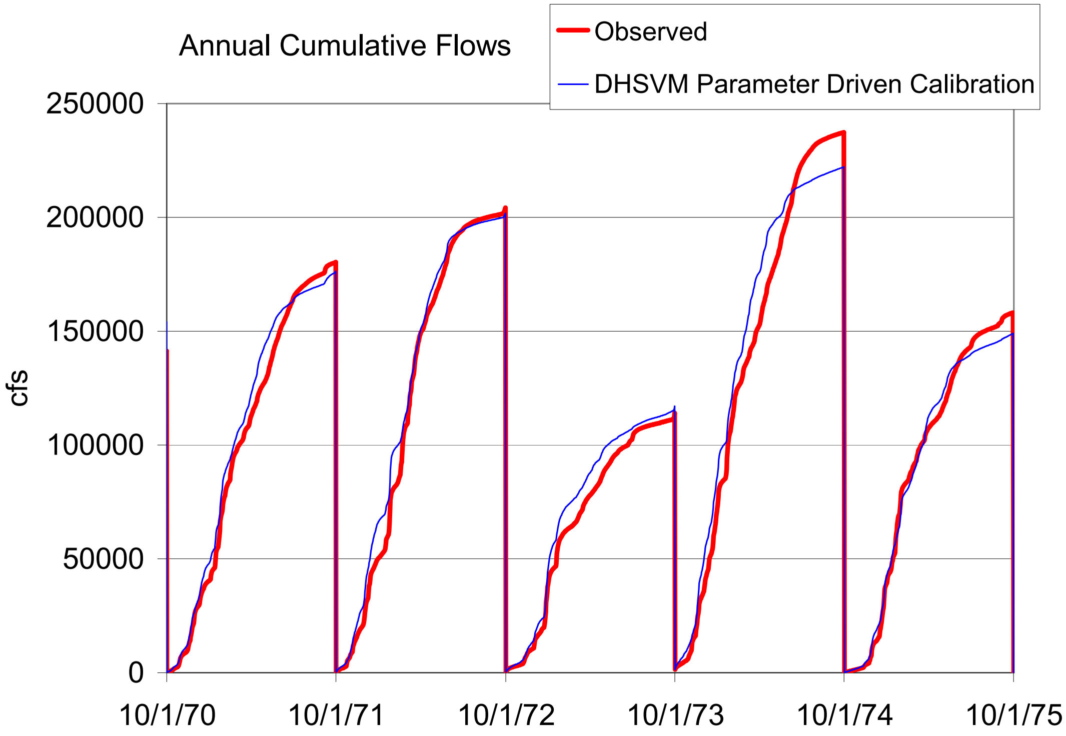


Figure 13. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1970-1975

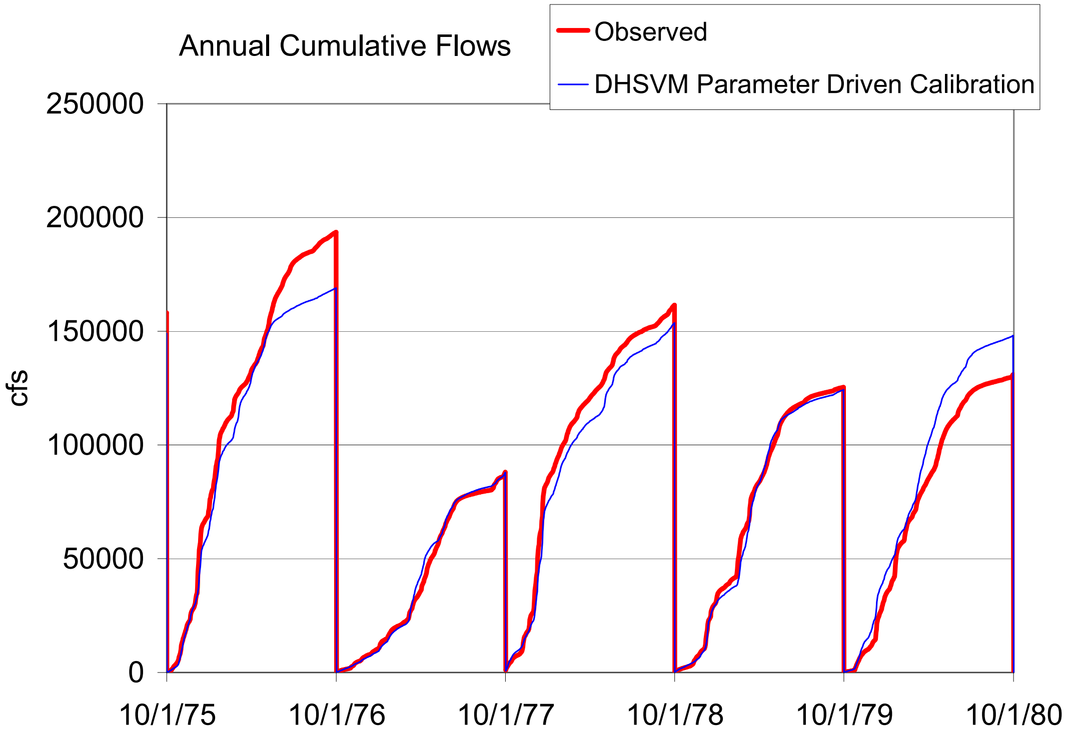


Figure 14. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1975-1980

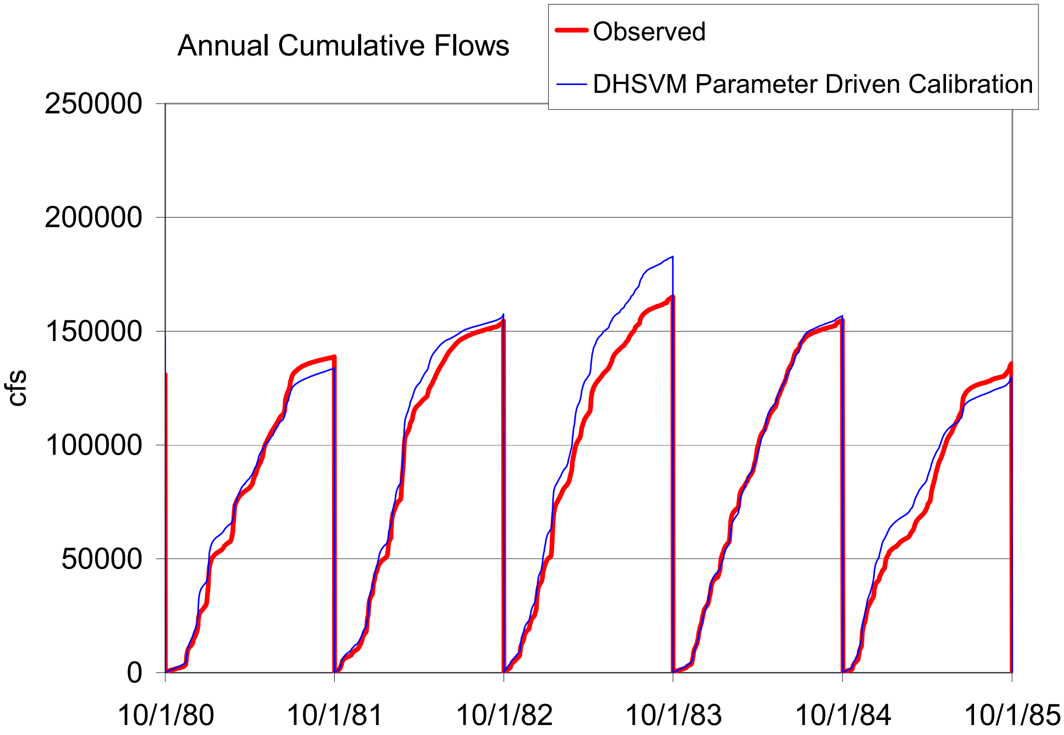


Figure 15. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1980-1985

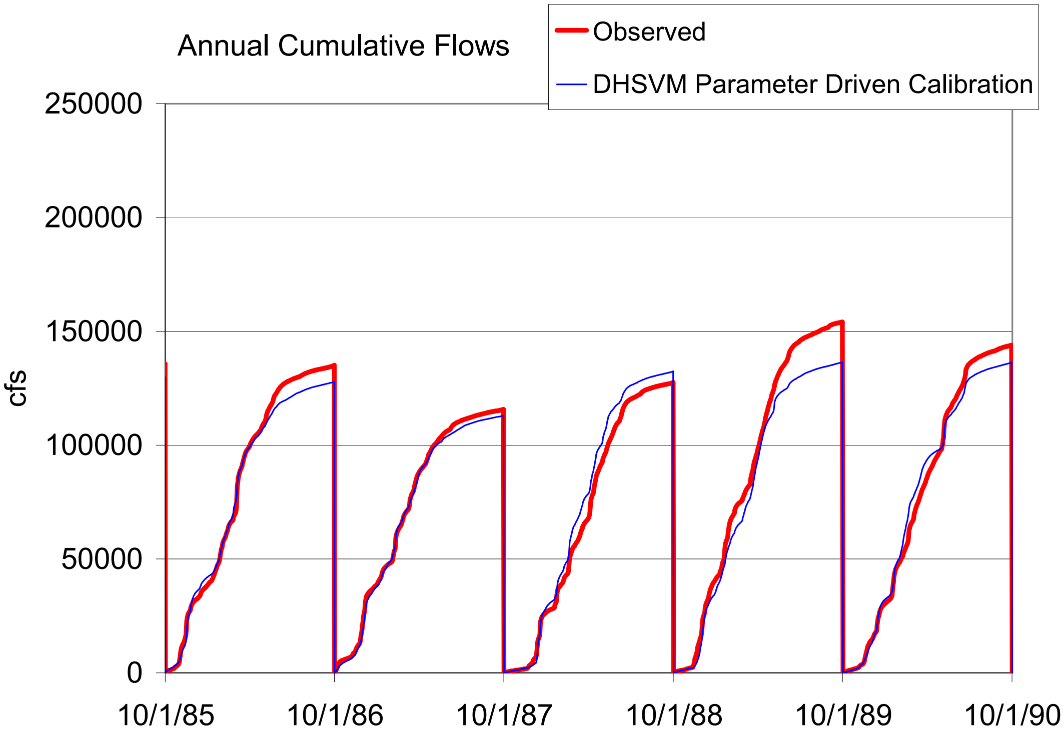


Figure 16. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1985-1990

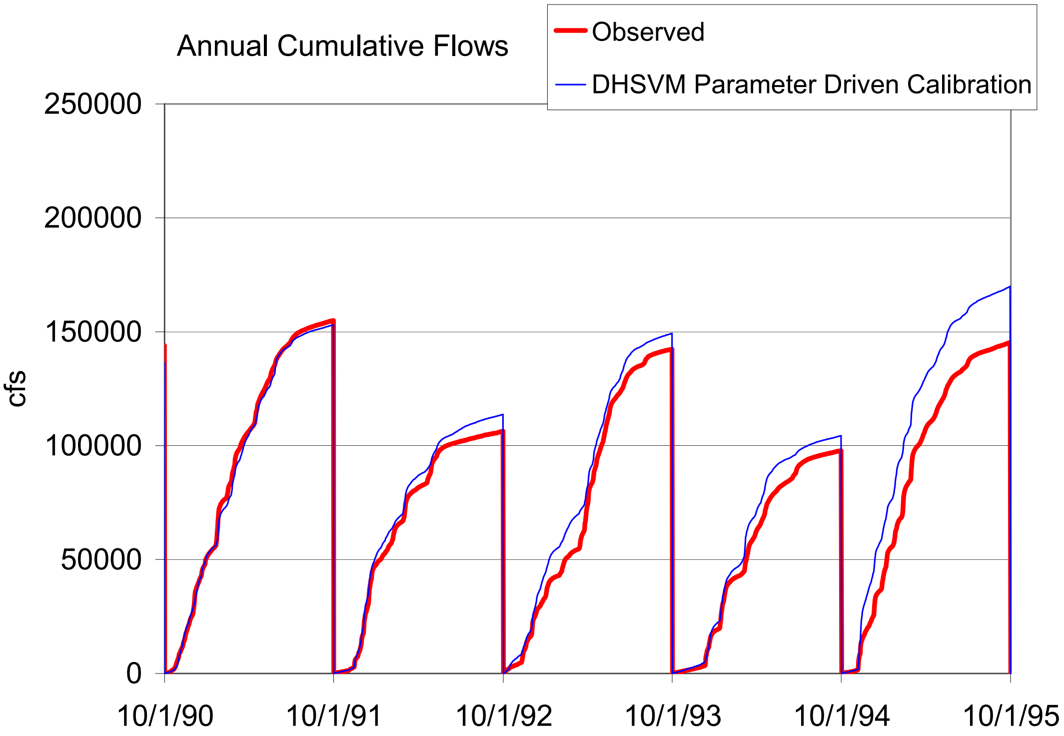


Figure 17. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1990-1995

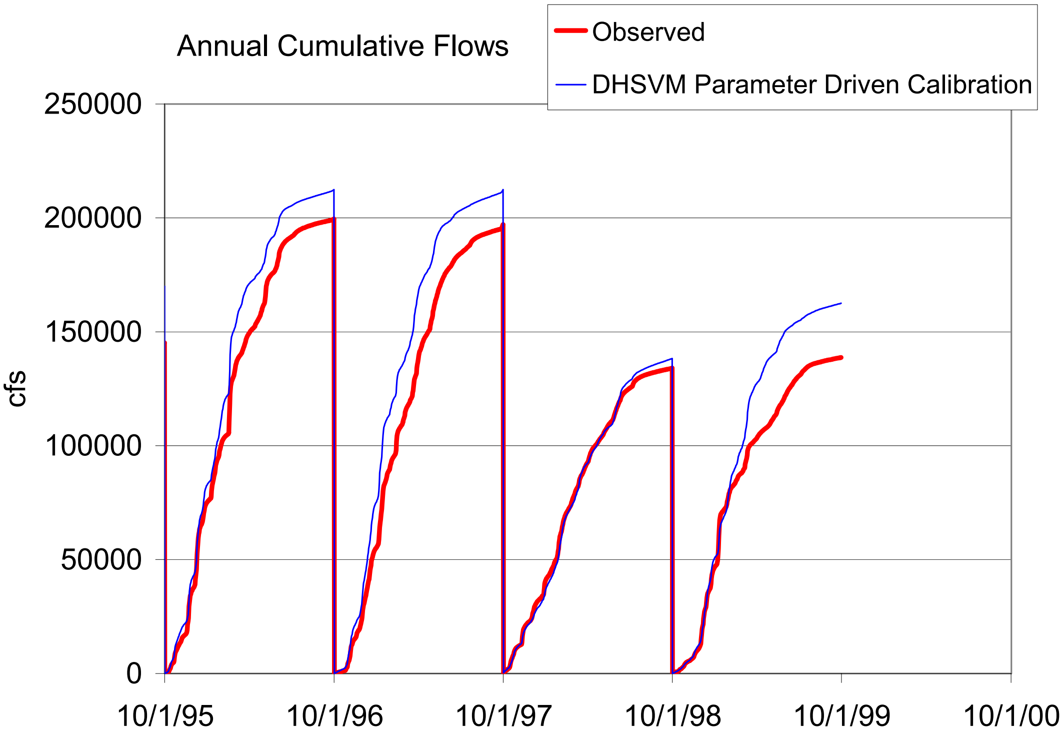


Figure 18. Annual Cumulative Flows, Bull Run Flows into Dam 1, 1992-1999

Time Series Hydrographs

The time series comparison of the observed and the DHSVM simulated Bull Run inflows into Dam 1 are shown in Figures 19-28.

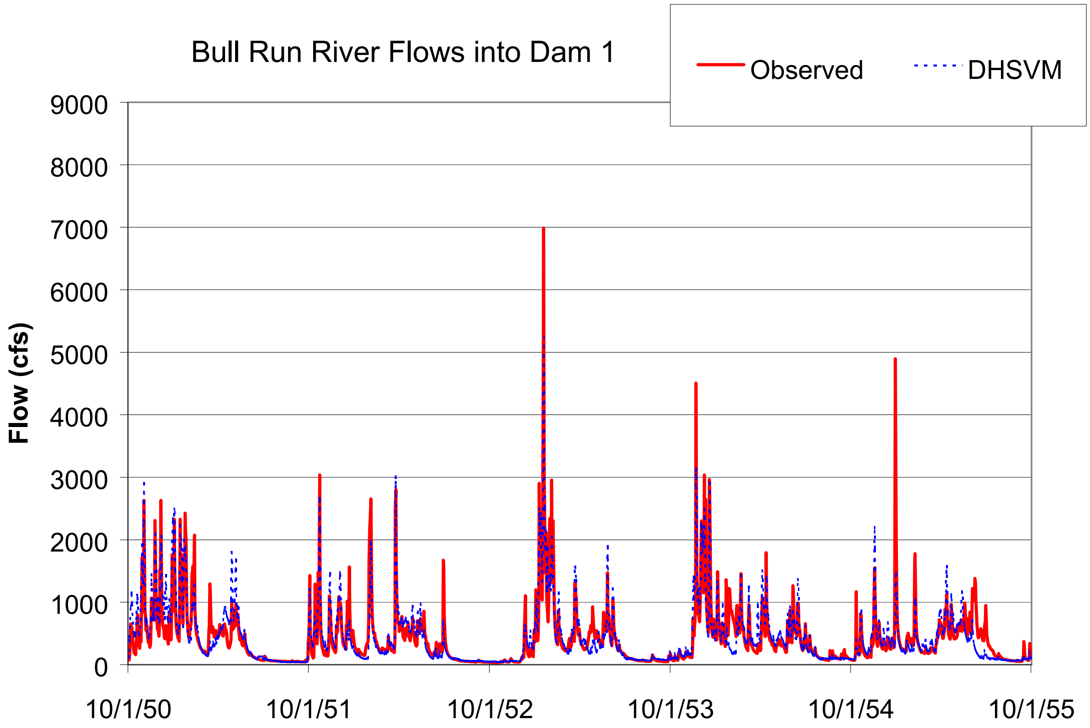


Figure 19. Bull Run Flows into Dam 1, 1950-1955

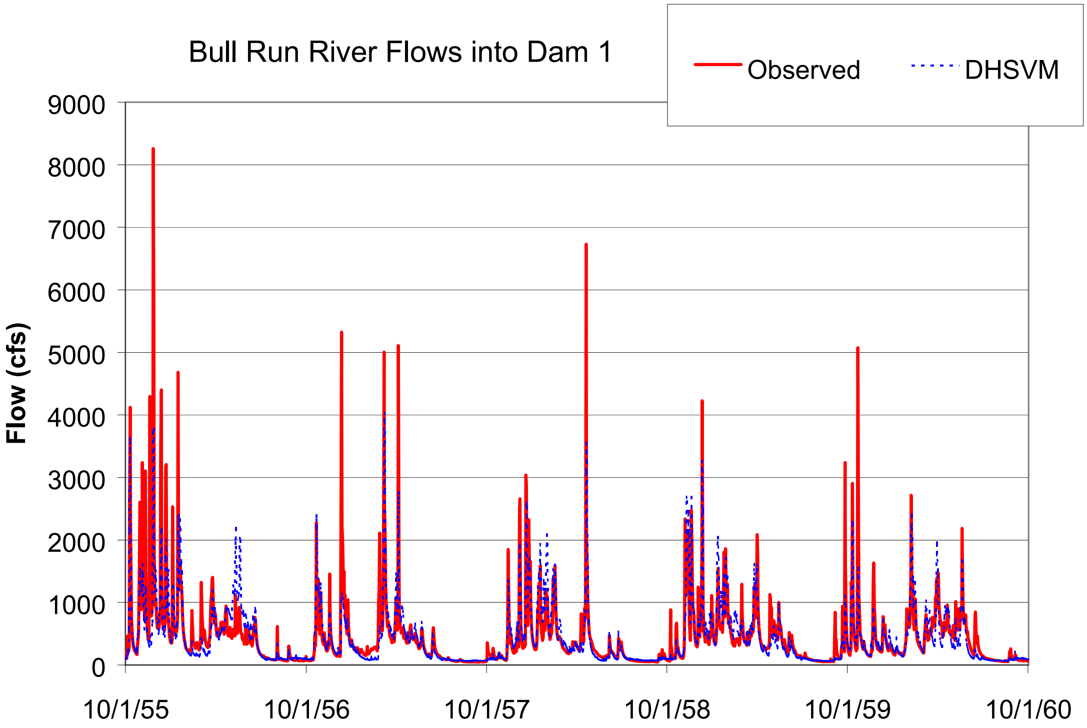


Figure 20. Bull Run Flows into Dam 1, 1955-1960

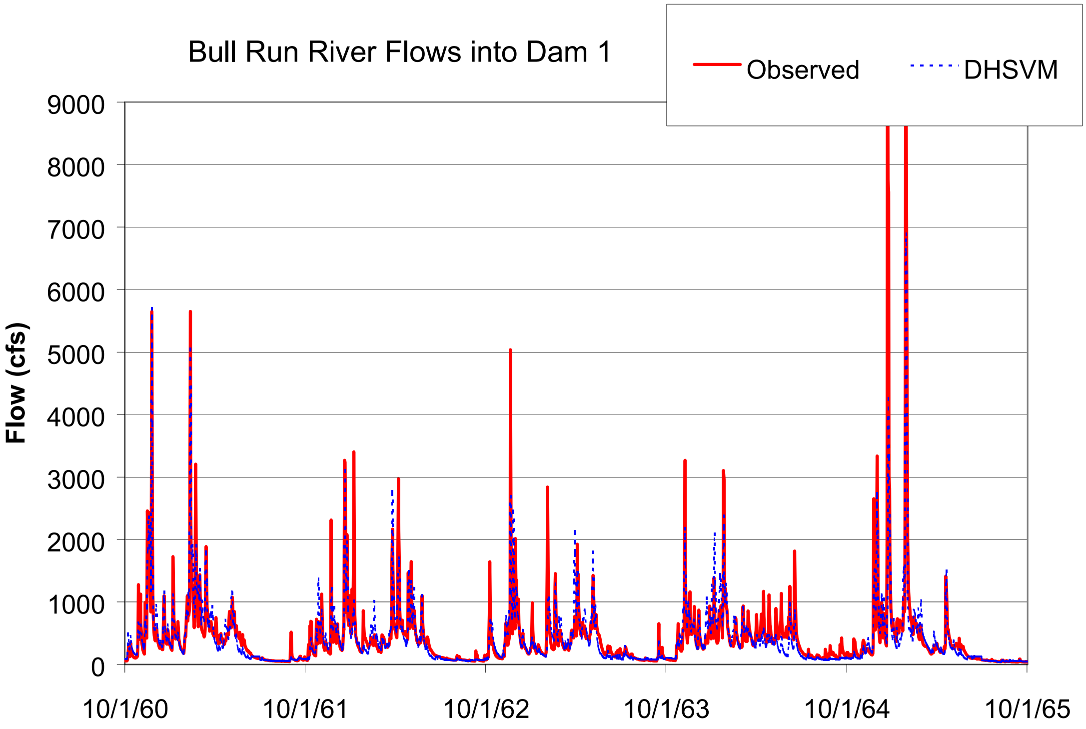


Figure 21. Bull Run Flows into Dam 1, 1960-1965

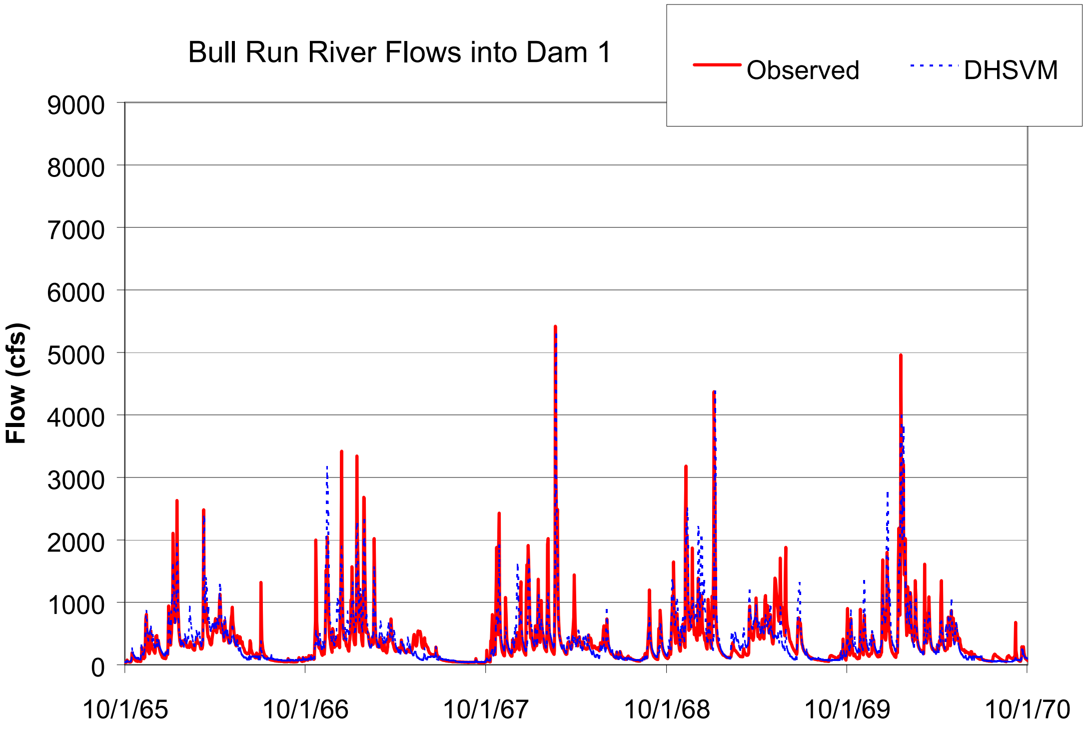


Figure 22. Bull Run Flows into Dam 1, 1965-1970

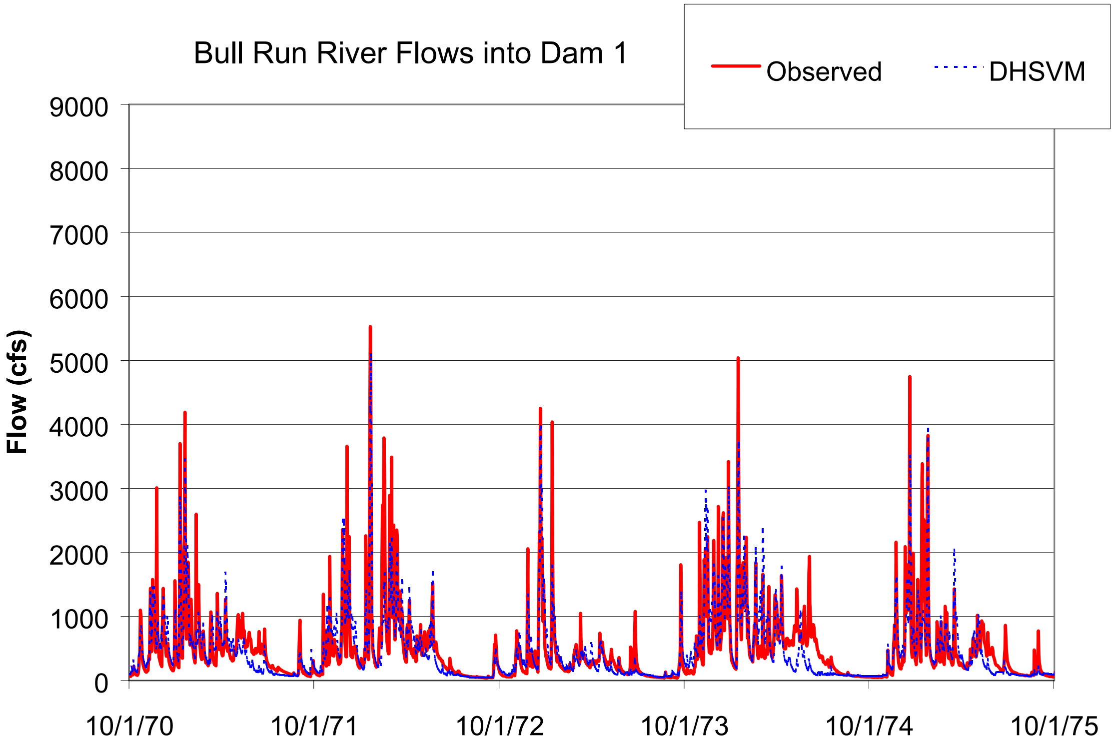


Figure 23. Bull Run Flows into Dam 1, 1970-1975

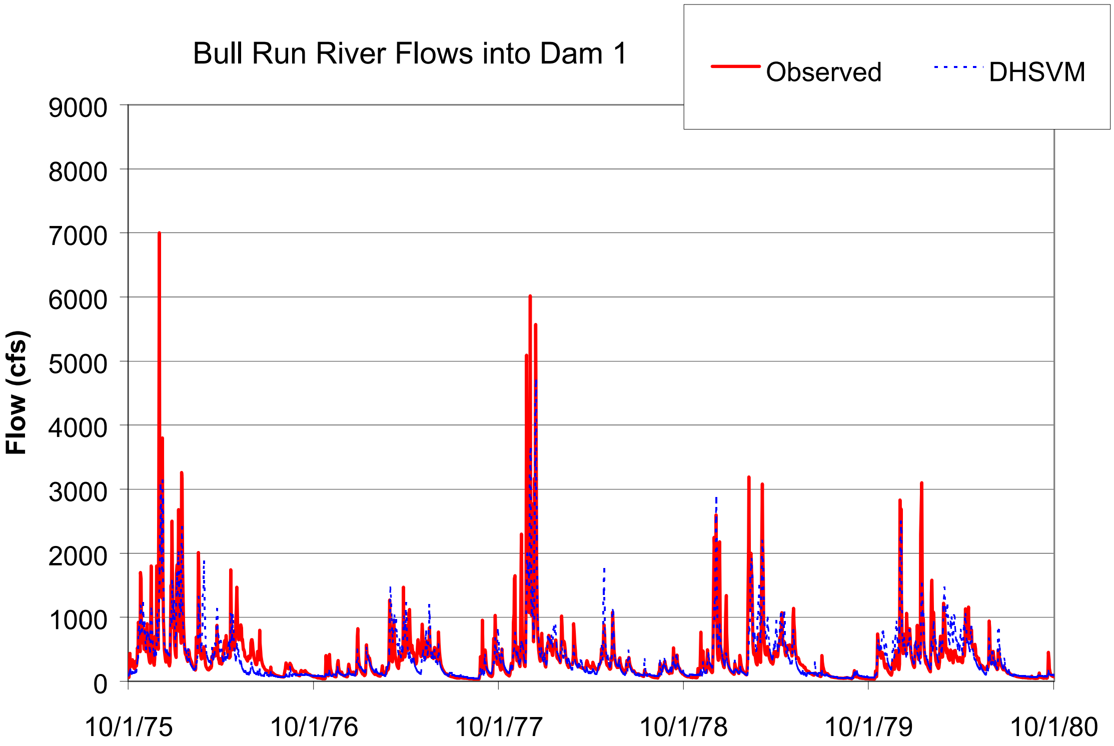


Figure 24. Bull Run Flows into Dam 1, 1975-1980

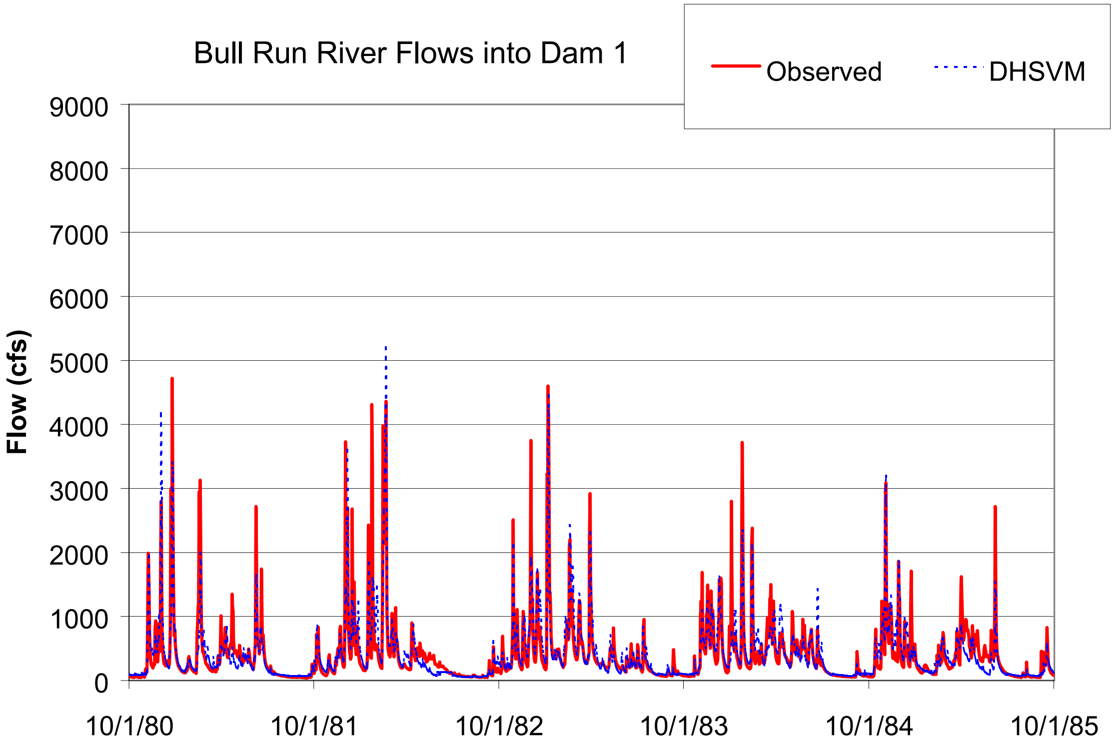


Figure 25. Bull Run Flows into Dam 1, 1980-1985

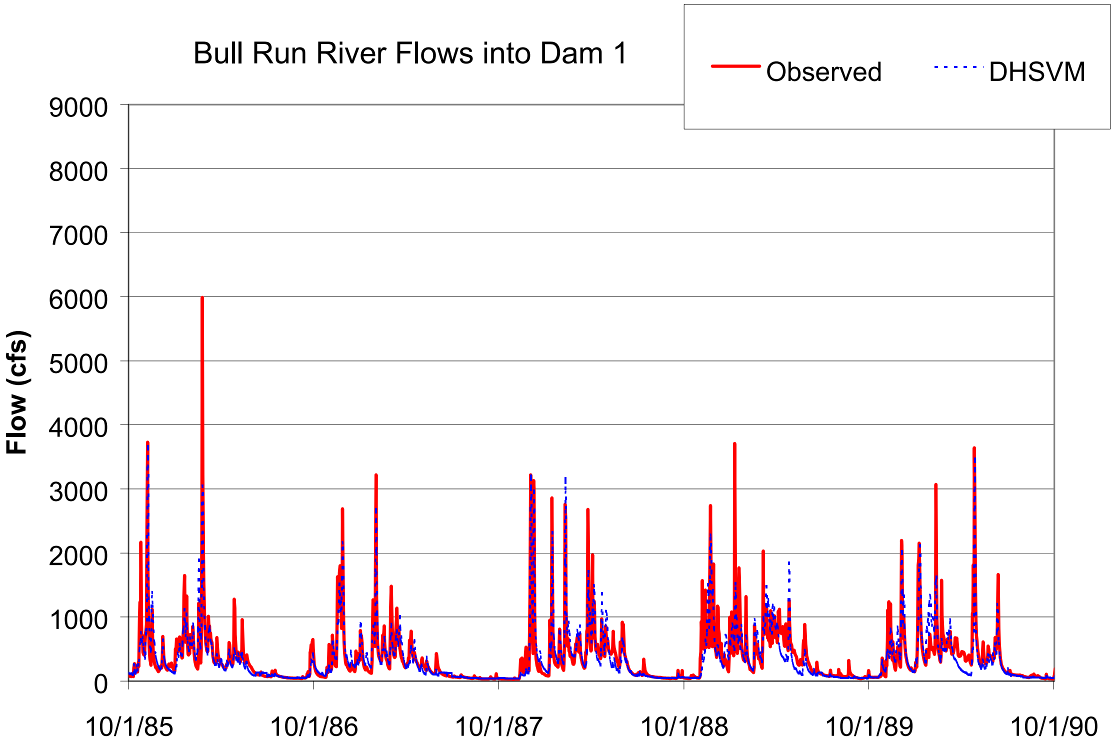


Figure 26. Bull Run Flows into Dam 1, 1985-1990

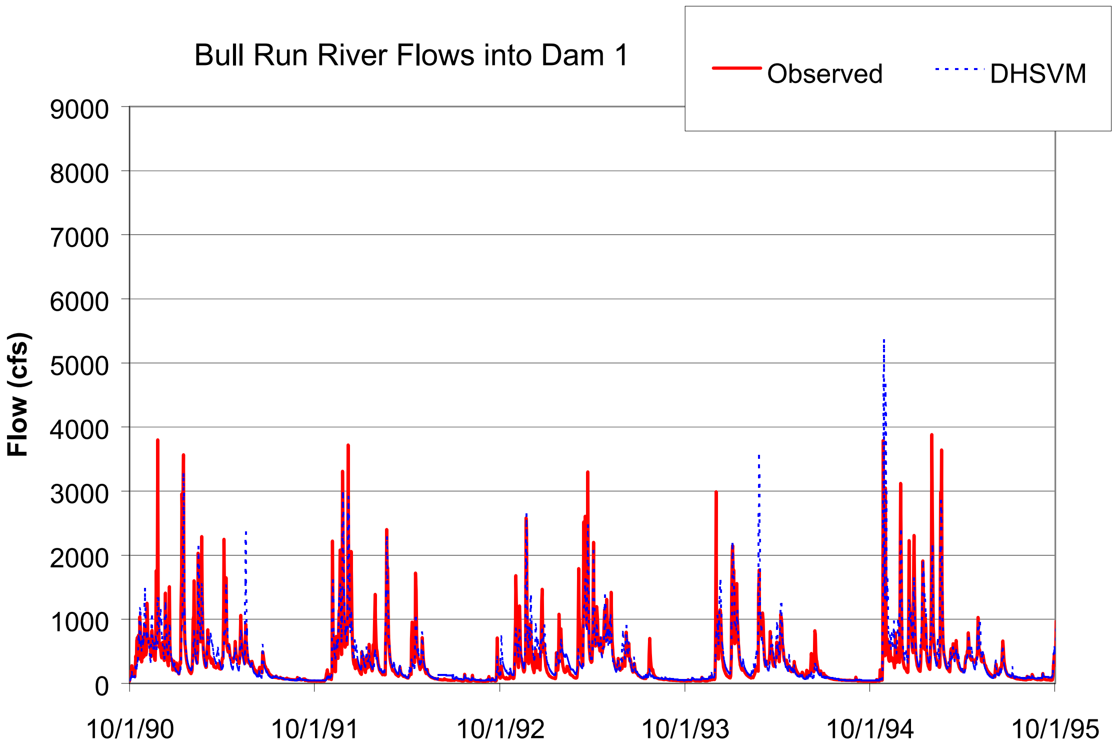


Figure 27. Bull Run Flows into Dam 1, 1990-1995

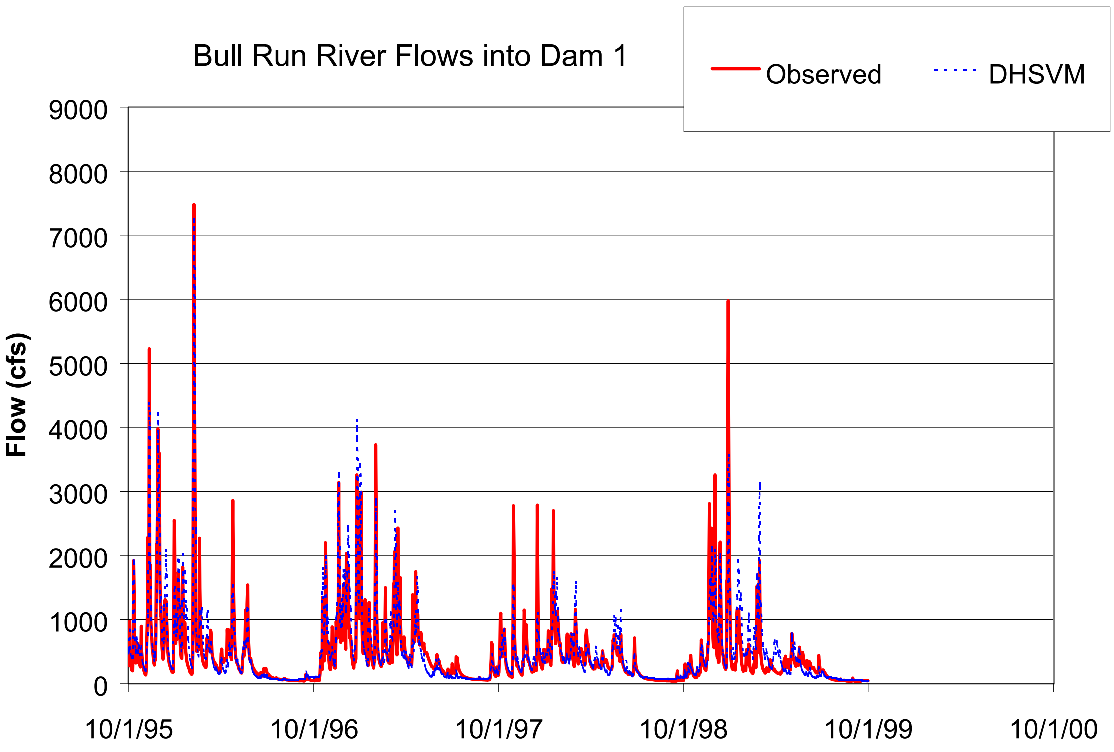


Figure 28. Bull Run Flows into Dam 1, 1995-1999

5. *Caveats*

Computer models of hydrologic systems are based on the concept that fundamental physical features can be parameterized, interactions between physical parameters can be estimated, and hydrologic outputs can be simulated to replicate what would happen in real systems. Such models have been in use for many decades and have seen wide application. A measure of the quality of such physical models has been the model's ability to replicate historic streamflows based on measurements in a watershed. This test of calibration is the one typically used to measure a model's success.

When working with watershed models, it is important to note that the ability to replicate past flows is both a function of the calibration process and the data available for calibration. In the Bull Run watershed, there is a paucity of meteorological data. Within the basin there is only one site that contains an extended record of rainfall and temperature. It is upon this single site that all of the meteorological data used in this calibration were derived. It is well know that there is significant spatial variability in both temperature and precipitation data. For this reason, single stations are likely to be unable to reflect all of the variability that occurs in a basin. This paucity of data places particular challenges on the degree to which any model can be reasonably expected to replicate historic streamflows.

As the calibration results in this report illustrate, there are periods in which the DHSVM model does an excellent job in replicating historic streamflows and periods in which the calibration is less than excellent. These differences arise most likely because during certain periods, the meteorological data being used is representative of that occurring over the entire watershed and at other times, due to spatial variability, the data being used is not characteristic of that occurring throughout the basin.

The calibrated DHSVM model is best at simulating the basin flows in the fall and winter. This is shown by the high r^2 values for the fall and winter months (October-March) in Table 2, the annual cumulative flows (Figures 9-18) and the time series hydrographs (Figures 19-28). The model is least successful in simulating flows in the spring and summer. In the spring months the model underestimates the flows as indicated in the average annual hydrograph (Figure 8), by the low r^2 values in the summer months (April-September) and in the time series of streamflows (Figures 19-28). The quality of the calibration results for the Bull Run basin are similar, if not superior, to those that we have experienced in other basins in the Pacific Northwest using the DHSVM model.

It is important to note that for the purpose of climate change, the DHSVM model will be able to simulate what would happen under specified climate conditions. This will not be limited by the meteorological data that are available. What will be important in the stages to come is the impact of changes in temperature and rainfall on streamflows, for which the DHSVM is well suited. The model will accurately and consistently evaluate what changes in streamflow will occur if temperature and precipitation change by specified amounts. The differences in the flows represented by DHSVM and the observed record noted here would have little impact on the relative change in flows between DHSVM for the current climate model results and the results of a climate change model run. The relative change in the current climate and altered climates will be applicable to existing water resource management decision-making strategies, which are based on the observed record.

It is the judgement of the authors that the DHSVM application is calibrated appropriately for an investigation of potential impacts of climate change. As in all calibration efforts of physical systems there remain areas in which further refinements could be made. Our success in calibrating the Bull Run watershed is superior to the calibration that we have achieved to date in the Sultan, Green and Tolt watersheds in the Puget Sound and is similar to those achieved in the Cedar River basin (where we have devoted significantly more efforts).

6. *References*

Daly, C., (1994). A statistical topographic model for mapping climatological precipitation over mountainous terrain, Journal of Applied Meteorology, 33(2):140-158.

Hahn, M. A., Palmer, R. N., Hamlet, A.F. and Storck, P. (2001). A Preliminary Analysis of the Impacts of Climate Change on the Reliability of the Seattle Water Supply. Proceedings of World Water and Environmental Resources Congress. Orlando, Florida, May 2001.

Storck, P. (2000). “Trees, Snow and Flooding: An Investigation of Forest Canopy Effects on Snow Accumulation and Melt at the Plot and Watershed Scales in the Pacific Northwest.” *Water Resources Series Technical Report No 161*, University of Washington.

Wigmosta, M. S., Vail, L. W., and Lettenmaier, D. P. (1994). “A Distributed Hydrology-Vegetation Model for Complex Terrain.” *Water Resources Research*, Vol. 30, No. 6, 1665-1678.

Appendix B – Figures and Tables

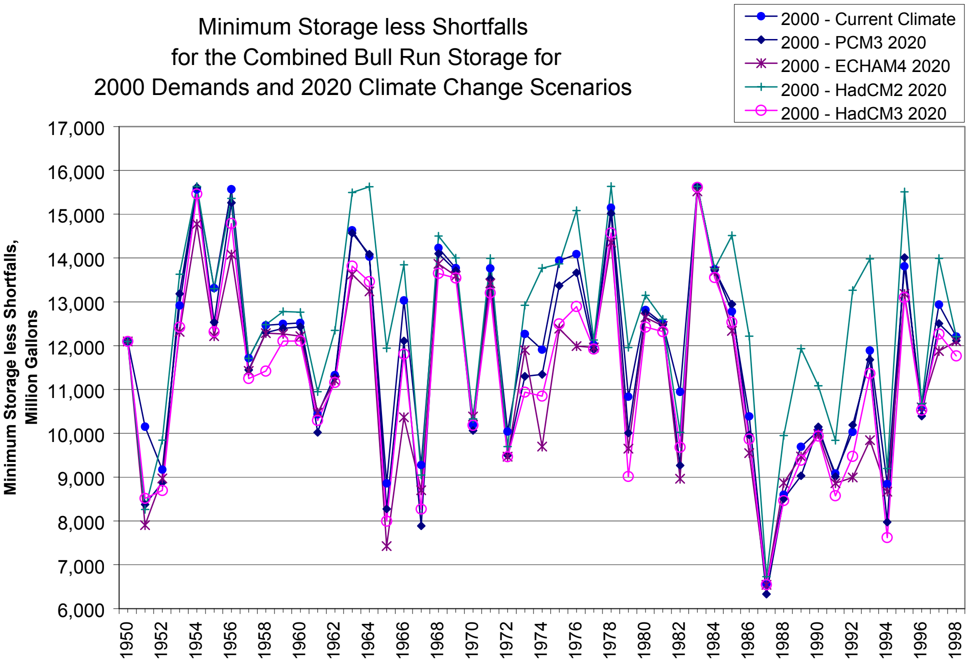


Figure 1 - Minimum Annual Storages less Shortfalls for the Combined Bull Run Storage for the 2000 Demands and 2020 Climate Change Scenarios

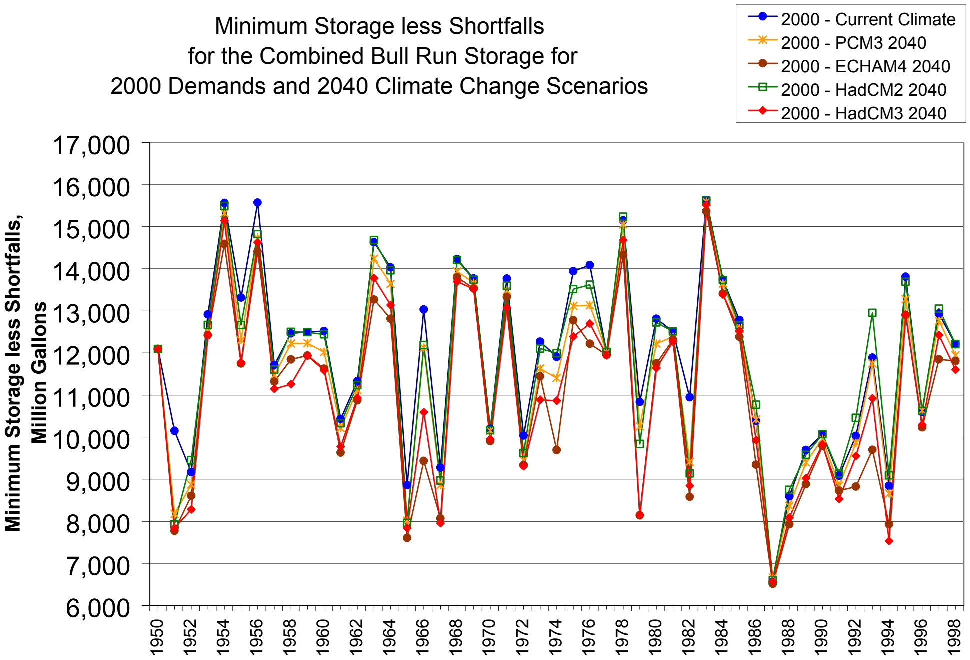


Figure 2 - Minimum Annual Storages less Shortfalls for the Combined Bull Run Storage for the 2000 Demands and 2020 Climate Change Scenarios

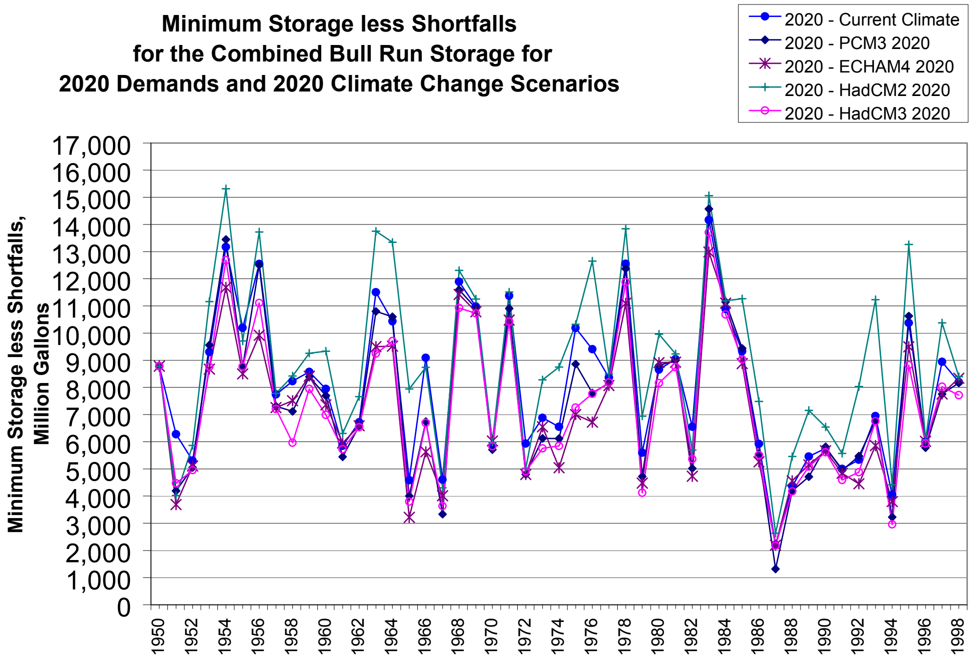


Figure 3 - Minimum Annual Storages less Shortfalls for the Combined Bull Run Storage for the 2000 Demands and 2020 Climate Change Scenarios

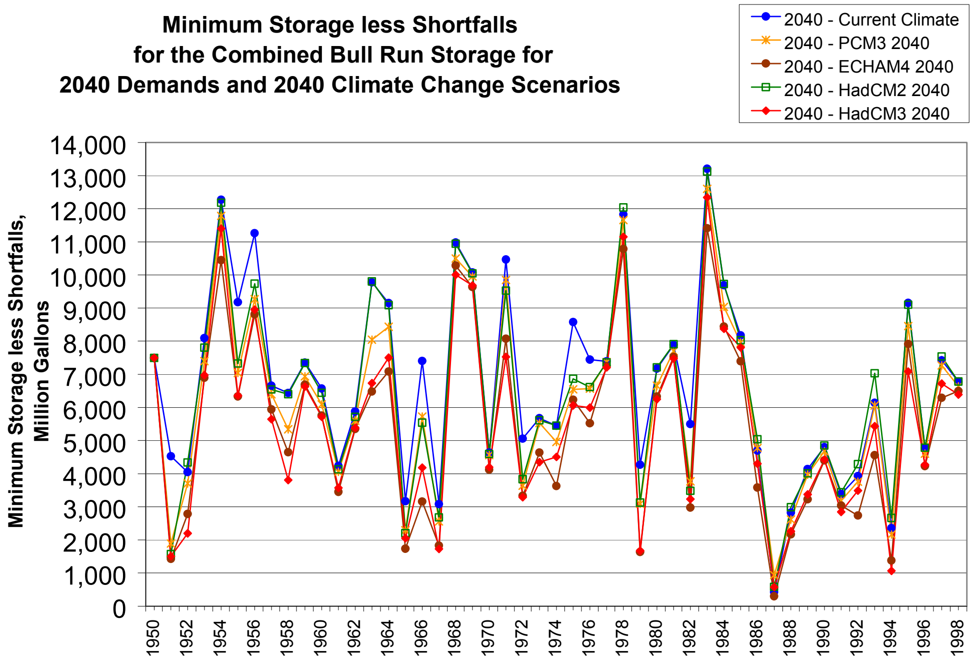


Figure 4 - Minimum Annual Storages less Shortfalls for the Combined Bull Run Storage for the 2000 Demands and 2020 Climate Change Scenarios

Table 1-B Metrics for the Scenario 2 System Configuration, Current Climate and Climate Change (ECHAM4) Hydrology and Demands

Scenario 2 System Configuration Metrics

Scenario 2 - Groundwater, 1952

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1952	7069	12232	1110	18585	3039	3040	91	196	190	109	0	0	4571	4722	151	20
2000	2020	1952	7411	8751	1260	18086	2696	2040	118	254	244	140	0	0	4570	4671	101	27
2000	2050	1952	10558	10602	1020	23002	2390	2580	125	272	263	150	0	14	4569	4697	128	19
2020	2020	1952	7763	10471	3270	22829	2345	2600	120	276	265	145	0	16	4568	4697	129	18
2050	2050	1952	10668	10069	2545	24740	2281	2600	127	302	292	157	0	122	4569	4698	129	18

Scenario 2 - Groundwater, 1966

Climate Scenario	Demand year	Calendar Year	Total Storage Used for	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1966	3911	11366	0	13441	6197	2040	92	178	176	108	0	0	9683	9784	101	61
2000	2020	1966	4226	11073	810	16952	5882	2000	119	233	230	139	0	0	9685	9784	99	59
2000	2050	1966	8214	11689	840	18947	4735	2080	126	249	245	149	0	0	9681	9784	103	46
2020	2020	1966	5887	18796	4760	28847	4221	5016	122	252	249	144	0	0	9619	9784	165	26
2050	2050	1966	8868	113042	5830	46883	2898	13043	129	275	272	157	0	39	9492	9775	283	10

Scenario 2 System Configuration Metrics

Scenario 2 - Groundwater, 1968

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1968	2664	6712	0	8006	7444	1080	87	198	184	106	0	0	10403	10456	53	140
2000	2020	1968	3360	6712	420	10347	6748	1080	112	256	240	136	0	0	10403	10456	53	127
2000	2050	1968	4080	6712	330	11057	8868	1080	119	266	253	145	0	4	10403	10456	53	167
2020	2020	1968	4046	6420	750	11518	6062	1120	115	275	258	141	0	6	10403	10458	55	110
2050	2050	1968	4855.43	10811.3	970.00	15,313.91	8093.25	1420	121.49	292.18	278.99	152.8	0	76.78	10403	10473	70	116

Scenario 2 - Groundwater, 1982

	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1982	3048	14034	2310	16344	7060	3382	91	186	181	108	0	0	15475	15594	119	59
2000	2020	1982	3176	14393	4620	21438	6932	3511	119	241	230	138	0	0	15473	15594	121	57
2000	2050	1982	7199	14590	4130	23077	5750	3576	125	250	248	148	0	0	15472	15594	122	47
2020	2020	1982	4662	13282	7200	24361	5446	4490	121	261	249	144	0	0	15456	15588	132	41
2050	2050	1982	7478	14827	7070	28707	5471	4770	128	278	274	156	0	42	15456	15602	146	37

Scenario 2 System Configuration Metrics

Scenario 2 - Groundwater, 1987

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1987	6897	9337	3650	18706	3211	2900	89	198	184	111.25	0	0	17333	17477	144	22
2000	2020	1987	7256	9635	6040	24527	2852	2940	115	251	236	143.14	0	0	17331	17477	146	20
2000	2050	1987	10007	12755	5500	29610	2942	3389	122	274	254	153.07	0	10.77	17318	17484	166	18
2020	2020	1987	7552.41	14593.7	8105	31413.91	2555.39	3977	117.86	271.35	255.47	148.24	0	7.8	17295	17473	178	14
2050	2050	1987	10499.9	144167	7,890	34,179	2448.82	3932	124.54	302.59	281.4	160.64	0	83.64	17296	17474	178	14

Scenario2 – Groundwater, 1992

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1992	4298	9718	1960	14610	5809	2000	91	203	195	112	0	0	19150	19249	99	59
2000	2020	1992	4820	14403	5320	24813	5287	3139	118	264	252	144	0	3	19114	19249	135	39
2000	2050	1992	6953	14101	4820	26212	5996	3074	125	274	266	154	0	20	19116	19249	133	45
2020	2020	1992	5720	13441	6970	26253	4387	3139	120	284	271	149	0	24	19114	19249	135	32
2050	2050	1992	8744	13485	6810	29701	4205	3266	127	301	293	162	0	145	19115	19257	142	30

Scenario 2 System Configuration Metrics

Scenario 2 – Groundwater, 1994

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1994	7117	12431	910	16515	2991	2400	93	211	208	111	0	0	19891	20010	119	25
2000	2020	1994	7387	11525	3255	20053	2721	2260	121	273	268	143	0	9	19898	20010	112	24
2000	2050	1994	10059	21373	3985	31755	2890	5265	127	291	288	153	0	51	19837	20010	173	17
2020	2020	1994	7499	16819	6105	30051	2609	5040	123	293	288	148	0	47	19838	20002	164	16
2050	2050	1994	10117	16616	7260	33643	2832	5205	130	320	316	161	0	157	19837	20007	170	17

Table 2-B Metrics for the Scenario 3 System Configuration, Current Climate and Climate Change (ECHAM4) Hydrology and Demands

Scenario 3 – Dam 3 System Configuration Metrics

Scenario 3 - Dam 3, 1952

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1952	7189	12448	1020	18710	2919	3060	91	194	188	109	0	0	4571	4723	152	19
2000	2020	1952	13790	14308	0	25116	15318	3180	118	251	240	140	0	145	4568	4726	158	97
2000	2050	1952	15445	14308	0	26844	13663	3180	125	268	260	150	0	354	4568	4726	158	86
2020	2020	1952	15194	22309	0	33158	13914	5026	121	272	261	146	0	351	4524	4723	199	70
2050	2050	1952	19184	23281	0	37443	9924	5499	128	298	289	158	0	776	4517	4724	207	48

Scenario 3 - Dam 3, 1966

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1966	3913	11366	0	13440	6195	2040	92	177	174	108	0	0	9683	9784	101	61
2000	2020	1966	8401	20789	0	24796	20707	3763	120	231	228	140	0	63	9639	9786	147	141
2000	2050	1966	9915	21548	0	26988	19193	3957	126	246	243	149	0	257	9636	9786	150	128
2020	2020	1966	14159	21383	0	30168	14948	5508	122	250	246	145	0	258	9612	9786	174	86
2050	2050	1966	18221	20285	0	33803	10887	5762	129	273	269	158	0	714	9609	9789	180	60

Scenario 3 – Dam 3 System Configuration Metrics

Scenario 3 - Dam 3, 1968

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1968	2667	6712	0	8006	7441	1080	88	195	183	106	0	0	10403	10456	53	140
2000	2020	1968	5029	10906	0	13544	24079	1505	114	251	237	136	0	100	10386	10458	72	334
2000	2050	1968	5843	10906	0	14468	23265	1505	121	261	249	145	0	276	10386	10458	72	323
2020	2020	1968	6658	16209	0	19091	22450	2288	118	270	255	141	0	283	10381	10481	100	224
2050	2050	1968	8036	11481	0	17017	21072	1848	124	287	276	15	0	675	10381	10459	78	270

Scenario 3 - Dam 3, 1982

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1982	3054	14034	2310	16345	7054	3382	91	184	180	108	0	0	15475	15594	119	59
2000	2020	1982	10649	14801	0	21742	18459	3640	119	238	228	138	0	72	15471	15594	123	150
2000	2050	1982	12119	14801	0	23241	16989	3640	126	249	246	148	0	256	15471	15594	123	138
2020	2020	1982	14556	17136	0	26046	14552	4997	122	258	247	144	0	251	15450	15594	144	101
2050	2050	1982	17590	18702	0	31628	11517	5571	129	275	272	157	0	675	15447	15613	166	69

Scenario 3 – Dam 3 System Configuration Metrics

Scenario 3 - Dam 3, 1987

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1987	6901	9337	3720	18785	3207	2900	88	195	183	111.71	0	0	17333	17477	144	22
2000	2020	1987	17905	21031	0	34259	11203	5287	114	246	234	143.86	0	102.27	17280	17490	210	53
2000	2050	1987	20069	21225	0	36756	9039	5351	121	269	252	153.86	0	320.85	17279	17490	211	43
2020	2020	1987	19515	18251	0	34110	9593	4511	117	266	253	150	0	291	17292	17490	198	48
2050	2050	1987	22746	23289	0.00	40587	6362	5888	124	297	279	162	0	851	17271	17491	220	29

Scenario 3 - Dam 3, 1992

Climate Scenario	Demand year	Calendar Year	Total Storage Used for POA	Cum Inflow for DD	Cum GW Used for DD	Cum Demand for DD	Min Storage Remaining for POA	Cum Fish Flow for DD	Running 3 day Average for POA	Max Day Demand for POA	Max 3-Day Demand for POA	Average Demand for POA	Supply Shortfall Vol	Trans Shortfall Vol	Drawdown Start	Drawdown Finish	Number of Days of Drawdown	Min Storage per # days of Drawdown
2000	2000	1992	4308	9718	1960	14619	5800	2000	91	199	192	112	0	0	19150	19249	99	59
2000	2020	1992	13150	14637	0	25030	15957	3159	119	260	248	145	0	196	19114	19250	136	117
2000	2050	1992	14854	14403	0	26617	14253	3139	125	270	262	155	0	482	19114	19249	135	106
2020	2020	1992	15673	13441	0	26402	13435	3139	122	280	267	150	0	456	19114	19249	135	100
2050	2050	1992	18655	18352	0	33818	10453	3839	129	297	289	163	0	1009	19114	19284	170	61

Scenario 3 – Dam 3 System Configuration Metrics																		
Scenario 3 - Dam 3, 1994																		
Climate Scenario	**Demand year**	**Calendar Year**	**Total Storage Used for POA**	**Cum Inflow for DD**	**Cum GW Used for DD**	**Cum Demand for DD**	**Min Storage Remaining for POA**	**Cum Fish Flow for DD**	**Running 3 day Average for POA**	**Max Day Demand for POA**	**Max 3-Day Demand for POA**	**Average Demand for POA**	**Supply Shortfall Vol**	**Trans Shortfall Vol**	**Drawdown Start**	**Drawdown Finish**	**Number of Days of Drawdown**	**Min Storage per # days of Drawdown**
2000	2000	1994	7155	12431	910	16554	2953	2400	94	209	206	111	0	0	19891	20010	119	25
2000	2020	1994	15330	27625	0	29914	13778	5285	122	269	265	143	0	228	19837	20011	174	79
2000	2050	1994	17382	27831	0	32135	11726	5350	129	288	284	153	0	519	19836	20011	175	67
2020	2020	1994	17281	26949	0	31485	11826	5285	125	290	284	149	0	498	19837	20011	174	68
2050	2050	1994	20958	22870	0	34567	8150	5350	132	316	312	162	0	1057	19836	20011	175	47

Appendix C – System Configurations

System Configuration 1 (SC1) Status Quo without Groundwater

Source	Default settings	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2060**
GW (OFF/ON)	1	0	0	0	0	0	0	0	0	0	0	0	0
User Defined (OFF=0/ON=1)	1	0	0	0	0	0	0	0	0	0	0	0	0
Days of Supply Remaining (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
Groundwater Table (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rate (UD,DSR, or GWT)	UD	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR
Native GW Max Capacity (70 or 90)	70	70	70	70	70	70	70	70	70	70	70	70	90
ASR	4800	0	0	0	0	0	0	0	0	0	0	0	3400
Native	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600
Dam 1													
top	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1049
bottom	960	960	960	960	960	960	960	960	960	960	960	960	960
Dam 2													
top	860	860	860	860	860	860	860	860	860	860	860	860	872
bottom	842	842	842	842	842	842	842	842	842	842	842	842	816
Dam 3 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
BRL (OFF=0/ON=1)	1	1	1	1	1	1	1	1	1	1	1	1	1
Clackamas (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 30)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Existing Wells (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 10)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
JWC Source (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1

System Configuration 1 (SC1)	Status Quo without Groundwater												
rate (0 - 10)	0	10	10	10	10	10	10	10	10	10	10	10	10
calendar day start	151	1	1	1	1	1	1	1	1	1	1	1	1
calendar day stop	273	365	365	365	365	365	365	365	365	365	365	365	365
West Side ASR (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	1
rate (0 - 10)	0	0	0	0	0	0	0	0	0	0	0	0	20
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	320
Powell Valley ASR (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 20)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Powell Butte (50-200)	50	50	50	50	50	50	50	50	50	50	50	50	100
Transmission													
N1 to Z1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
Z1 to X1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
WCSL2 (OFF/ON)	0	0	0	0	0	0	0	0	0	0	0	0	0
capacity (0 - 70)	0	0	0	0	0	0	0	0	0	0	0	0	0
Conduit 5 (OFF/ON)	0	0	0	0	0	0	0	0	0	0	0	0	1
capacity (204 - 450)	204	204	204	204	204	204	204	204	204	204	204	204	450
Demands													
S1 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
A2 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
Z1 (OFF=0/ON=1)	1	1	1	1	1	1	1	1	1	1	1	1	1
TVWD													
WP (0.0-1.0, TVWD demands must sum to 1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
I1 (0.0-1.0, TVWD demands must sum to 1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

System Configuration 1 (SC1)	Status Quo without Groundwater												
N1 (0.0-1.0, TVWD demands must sum to 1)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Tigard													
I1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0	0
V1 (0.0-1.0, Tigard demands must sum to 1)	0.34	0	0	0	0	0	0	0	0	0	0	0	0
W1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0	0
Z1 (0.0-1.0, Tigard demands must sum to 1)	0	1	1	1	1	1	1	1	1	1	1	1	1
Programmatic Conservation (None, Medium, Full)	None	None	None	None	None	None	None	None	None	None	None	None	None

System Configuration (SC3) Baseline with Groundwater and System Expansion

Source	Default settings	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2060**
GW (OFF/ON)	1	1	1	1	1	1	1	1	1	1	1	1	1
User Defined (OFF=0/ON=1)	1	0	0	0	0	0	0	0	0	0	0	0	0
Days of Supply Remaining (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
Groundwater Table (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rate (UD,DSR, or GWT)	UD	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR
Native GW Max Capacity (70 or 90)	70	70	90	90	90	90	90	90	90	90	90	90	90
ASR	4800	0	3400	3400	3400	3400	3400	3400	3400	3400	3400	3400	3400
Native	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600
Dam 1													
top	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1049	1049
bottom	960	960	960	960	960	960	960	960	960	960	960	960	960
Dam 2													
top	860	860	860	860	860	860	860	860	860	860	860	872	872
bottom	842	842	842	842	842	842	842	842	842	842	842	842	842
Dam 3 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
BRL (OFF=0/ON=1)	1	1	1	1	1	1	1	1	1	1	1	1	1
Clackamas (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 30)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Existing Wells (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 10)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273

System Configuration (SC3) Baseline with Groundwater and System Expansion

JWC Source (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
rate (0 - 10)	0	10	10	10	10	10	10	10	10	10	10	10	10
calendar day start	151	1	1	1	1	1	1	1	1	1	1	1	1
calendar day stop	273	365	365	365	365	365	365	365	365	365	365	365	365
West Side ASR (OFF=0/ON=1)	0	0	1	1	1	1	1	1	1	1	1	1	1
rate (0 - 10)	0	0	5	10	10	20	20	20	20	20	20	20	20
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	320	320	320	320	320	320	320	320	320	320	320
Powell Valley ASR (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 20)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Powell Butte (50-200)	50	50	100	100	100	100	100	100	100	100	100	100	100
Transmission													
N1 to Z1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
Z1 to X1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
WCSL2 (OFF/ON)	0	0	0	0	0	0	0	0	0	0	0	0	0
capacity (0 - 70)	0	0	0	0	0	0	0	0	0	0	0	0	0
Conduit 5 (OFF/ON)	0	0	0	0	0	1	1	1	1	1	1	1	1
capacity (204 - 450)	204	204	204	204	204	227	227	227	227	227	227	450	450
Demands													
S1 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
A2 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
Z1 (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
TVWD WP (0.0-1.0, TVWD demands must sum to 1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

System Configuration (SC3)	Baseline with Groundwater and System Expansion												
I1 (0.0-1.0, TVWD demands must sum to 1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
N1 (0.0-1.0, TVWD demands must sum to 1)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Tigard													
I1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0	0
V1 (0.0-1.0, Tigard demands must sum to 1)	0.34	0	0	0	0	0	0	0	0	0	0	0	0
W1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0	0
Z1 (0.0-1.0, Tigard demands must sum to 1)	0	1	1	1	1	1	1	1	1	1	1	1	1
Programmatic Conservation (None, Medium, Full)	None	None	None	None	None	None	None	None	None	None	None	None	None

System Configuration 3 (SC3) Dam 3

Source	Default settings	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2060**
GW (OFF/ON)	1	1	1	1	1	0	0	0	0	0	0	0	0
User Defined (OFF=0/ON=1)	1	0	0	0	0	0	0	0	0	0	0	0	0
Days of Supply Remaining (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
Groundwater Table (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
supply rate (UD,DSR, or GWT)	UD	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR	DSR
Native GW Max Capacity (70 or 90)	70	70	90	90	90	90	90	90	90	90	90	90	90
ASR	4800	0	3400	3400	3400	3400	3400	3400	3400	3400	3400	3400	3400
Native	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600	6600
Dam 1													
top	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045	1045
bottom	960	960	960	960	960	960	960	960	960	960	960	960	960
Dam 2													
top	860	860	860	860	860	860	860	860	860	860	860	860	860
bottom	842	842	842	816	816	816	816	816	816	816	816	816	816
Dam 3 (OFF=0/ON=1)	0	0	0	0	0	1	1	1	1	1	1	1	1
BRL (OFF=0/ON=1)	1	1	1	1	1	0	0	0	0	0	0	0	0
Clackamas (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 30)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Existing Wells (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 10)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273

System Configuration 3 (SC3)	Dam 3												
JWC Source (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
rate (0 - 10)	0	10	10	10	10	10	10	10	10	10	10	10	10
calendar day start	151	0	0	0	0	0	0	0	0	0	0	0	0
calendar day stop	273	365	365	365	365	365	365	365	365	365	365	365	365
West Side ASR (OFF=0/ON=1)	0	0	1	1	1	0	0	0	0	0	0	0	0
rate (0 - 10)	0	0	5	10	10	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	320	320	320	320	320	320	320	320	320	320	320
Powell Valley ASR (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
rate (0 - 20)	0	0	0	0	0	0	0	0	0	0	0	0	0
calendar day start (1 - 365)	151	151	151	151	151	151	151	151	151	151	151	151	151
calendar day stop (1 - 365)	273	273	273	273	273	273	273	273	273	273	273	273	273
Powell Butte (50-200)	50	50	100	100	100	100	100	100	100	100	100	100	100
Transmission													
N1 to Z1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
Z1 to X1 capacity (0 - 60)	60	60	60	60	60	60	60	60	60	60	60	60	60
WCSL2 (OFF/ON)	0	0	0	0	0	0	0	0	0	0	0	0	0
capacity (0 - 70)	0	0	0	0	0	0	0	0	0	0	0	0	0
Conduit 5 (OFF/ON)	0	0	0	0	0	1	1	1	1	1	1	1	1
capacity (204 - 450)	204	204	204	204	204	450	450	450	450	450	450	450	450
Demands													
S1 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
A2 (OFF=0/ON=1)	0	0	0	0	0	0	0	0	0	0	0	0	0
Z1 (OFF=0/ON=1)	0	1	1	1	1	1	1	1	1	1	1	1	1
TVWD													
WP (0.0-1.0, TVWD demands must sum to 1)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
I1 (0.0-1.0, TVWD demands must sum	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

System Configuration 3 (SC3) Dam 3

to 1)												
N1 (0.0-1.0, TVWD demands must sum to 1)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Tigard												
I1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0
V1 (0.0-1.0, Tigard demands must sum to 1)	0.34	0	0	0	0	0	0	0	0	0	0	0
W1 (0.0-1.0, Tigard demands must sum to 1)	0.33	0	0	0	0	0	0	0	0	0	0	0
Z1 (0.0-1.0, Tigard demands must sum to 1)	0	1	1	1	1	1	1	1	1	1	1	1
Programmatic Conservation (None, Medium, Full)	Full	None	None	None	None	None	None	None	None	None	None	None